Prof Angelo Di Tommaso
Università di Bologna

Tecniche di rinforzo con materiali compositi appropriati alle costruzioni storiche

Tecniche di rinforzo
con materiali compositi appropriati
alle costruzioni storiche

1) Uno sguardo alle applicazioni pionieristiche

Motivazioni per una diffusione !

1) **Valore molto basso dei rapporti peso/rigidezza e peso/resistenza**
2) **Durabilità e ridotta manutenzione**

SE SI RISPETTA IL LIVELLO DI QUALITÀ RICHIESTO PER LA TECNOLOGIA

2) La possibilità di preservare
la concezione strutturale originale della costruzione
aumentando la prestazione strutturale del materiale storico
durante le azioni esterne eccezionalmente severe.

FINALIZZAZIONE DELLA **TECNICA** :

CONTRASTARE L'INSORGERE
di
Meccanismi di collasso
Durante le azioni esterne ***eccezionali***
(terremoti, bufere, nevicate, impatti, etc.).

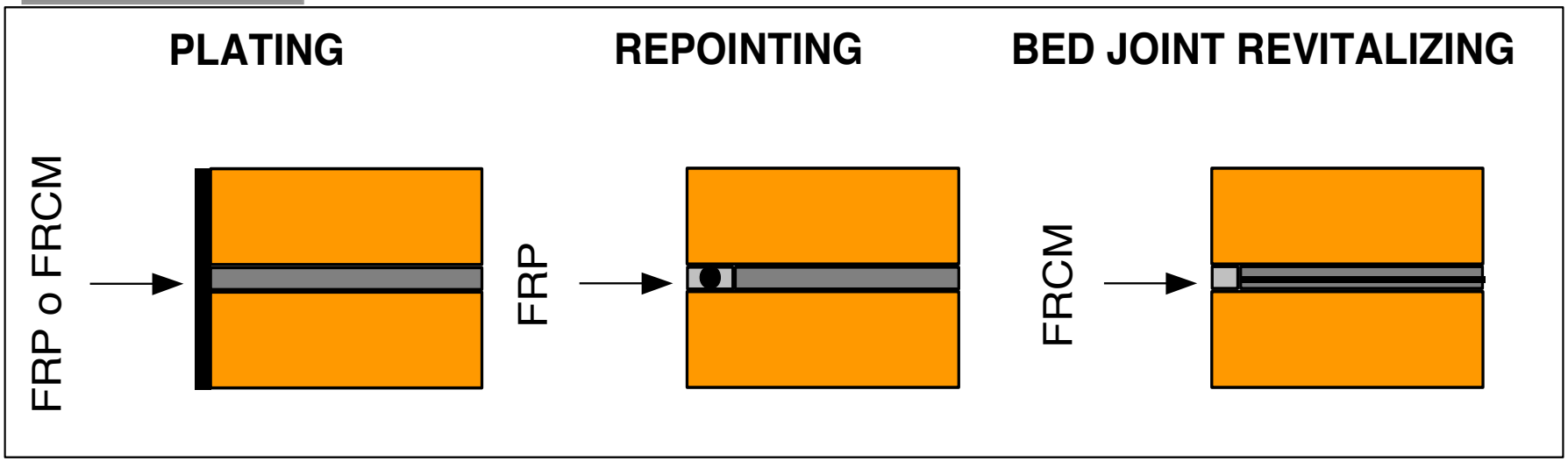
Tecniche per la muratura storica :

1) Placcaggio appropriato (Appropriate plating)
o Cinturazione (Belting)

2) Ristilatura armata (Reinforced Re-pointing)

3) Rivitalizzazione dei giunti di letto
(bed joint re-vitalisation) (FOR RE-CONSTRUCTION).

FUNDAMENTAL TECHNIQUES FOR HISTORICAL CONSTRUCTION STRENGTHENING with FRP or FRCM

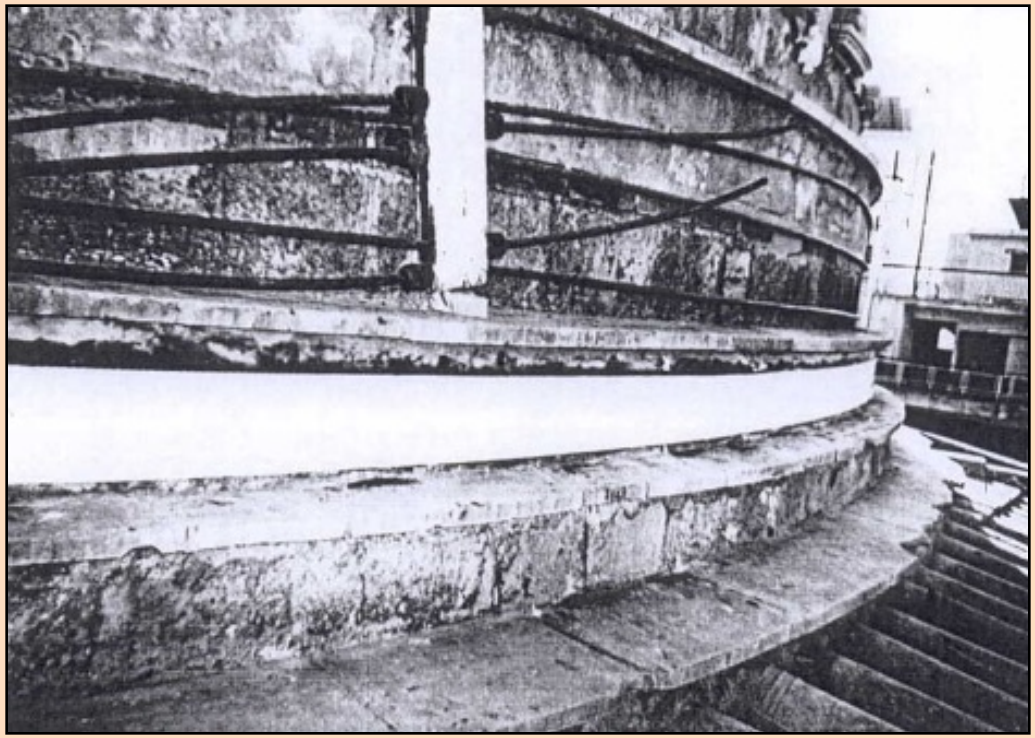


PLACCAGGIO RISTILATURA RIVITALIZZAZIONE DEL GIUNTO

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON *SOME* PIONEERING EPISODES

BELTING THE DRUM of the dome
Church Panaghia Faneromani

Aegeon (Grecia), 1996.



DRIVING ASPECTS

Aggressive environments

(No weight increase)

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION:
A LOOK ON *SOME* PIONEERING EPISODES

Masonry Building

Zurich (Switzerland), **1996.**

Application on vertical masonry wall

Previous timber decks substitution and elevator walls braced with cFRP Laminae

cFRP glued LAMINAE

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON *SOME* PIONEERING EPISODES

Cathedral Città di Castello

(Perugia, Italia),

May 1997,

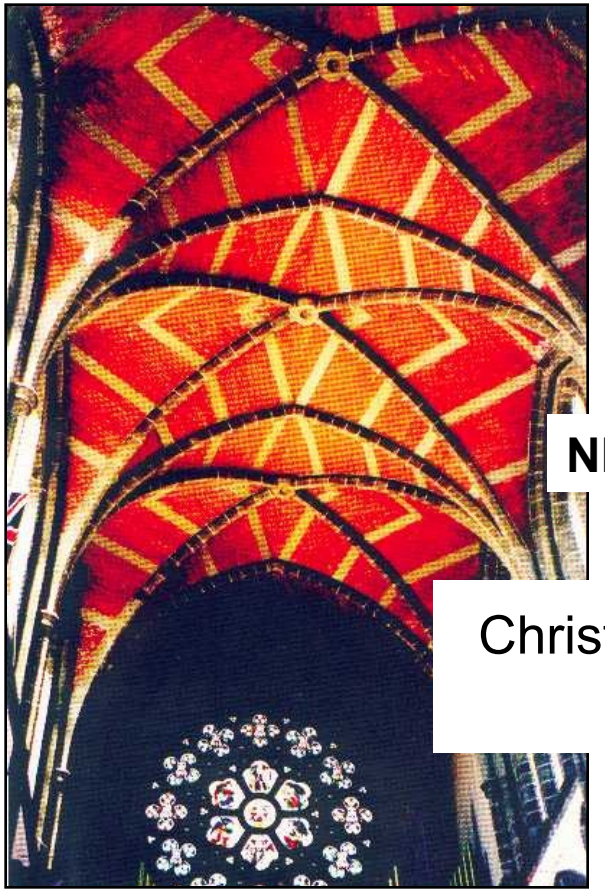
Belting Dome with cFRP.

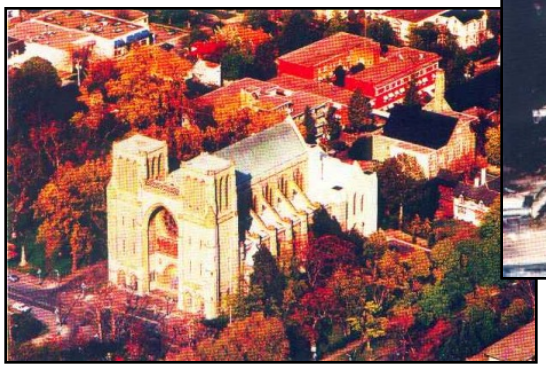
PLATING / BELTING TECHNIQUE

BEFORE Earthquake-**September 26th.1997**.

Ing G. Celestini TEC-INN PG

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION:
A LOOK ON *SOME* PIONEERING EPISODES





NEO-GOTHIC CROSS VAULTS OF THE NAVE

“BRICK RAIN”

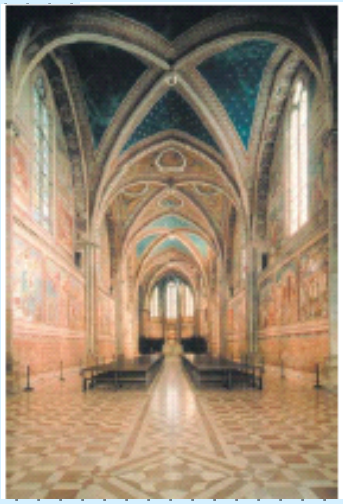
Christ Church Cathedral, British Columbia, Victoria
Canada, **1997**.

1997

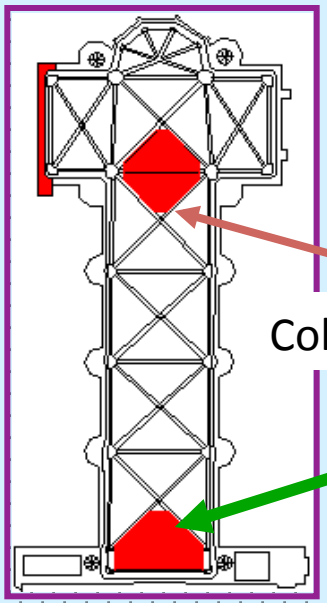
PLATED IN EXTRADOS

gFRP

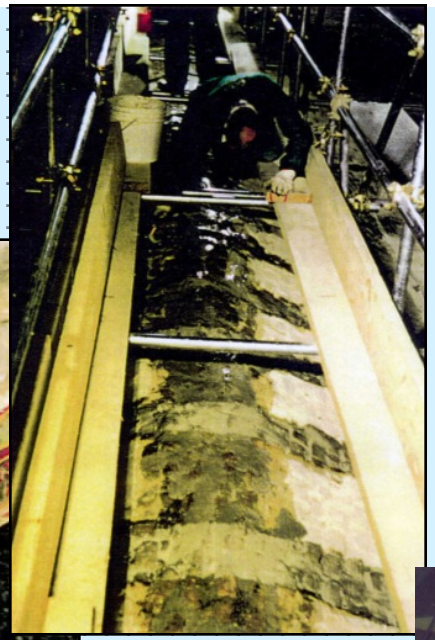
COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON *SOME* PIONEERING EPISODES

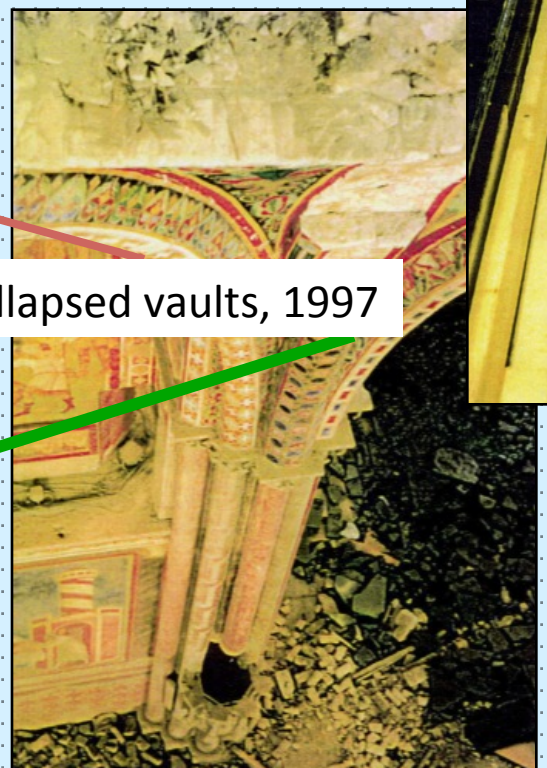


1997 Sept 26th strong earthquake in Umbria,
several interventions on the
Basilica of San Francesco in Assisi
with cFRP and aFRP
to sustain the partial collapsed gothic cross vaults



Collapsed vaults, 1997





- GLUE-LAM;
- MULTIDIRECTIONAL aFRP;
- PULTRUTED GLASS BARS;

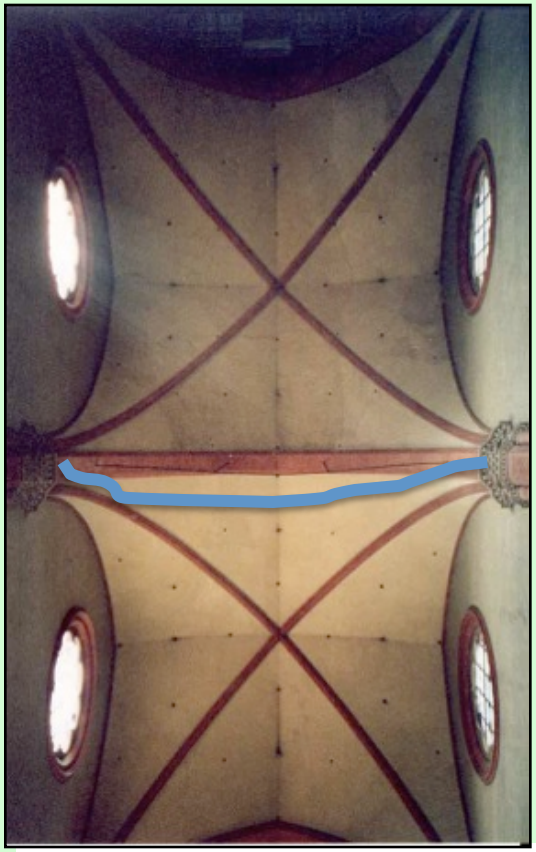
FRP plating

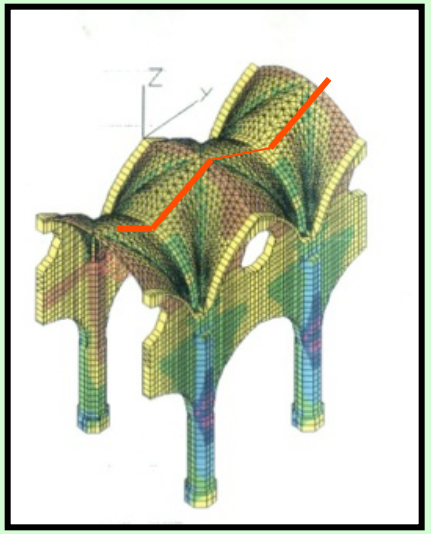
COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON *SOME* PIONEERING EPISODES

1999/2000 : Giubileo
reduction of vulnerability of huge cracked gothic vaults
technique of *appropriate plating* in extrados of all principal nave vaults .

All tie-rods deviated in compression

Basilica di San Petronio
Bologna (Italia), 1999.

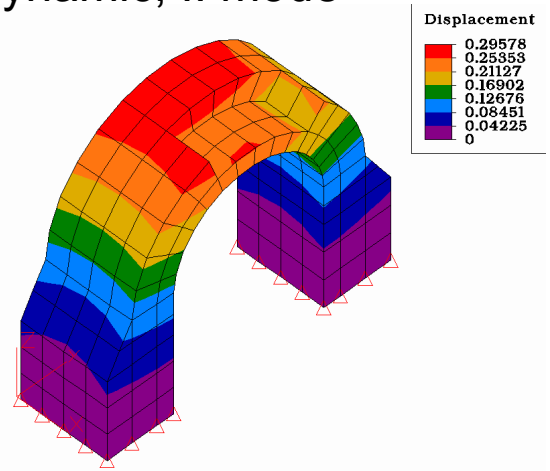




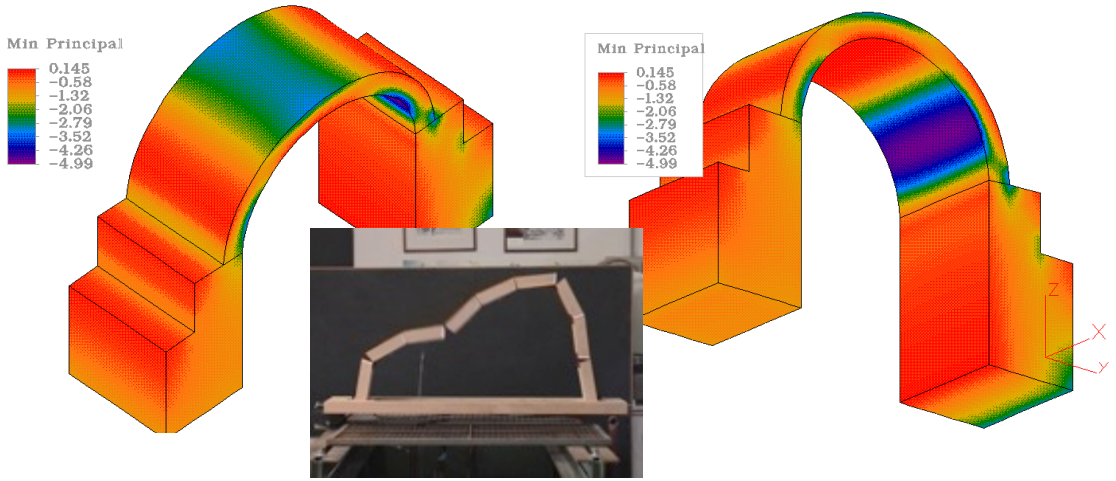
Continuos crack in estrados along all the nave

cFRP appropriate plating

Dynamic, II mode



Static horizontal forces (10% vertical w.)



Roman Arch in Rimini

FRCM *plating first ring.*

Cementitious matrix and reinforcing carbon net.

To contrast collapse mechanisms (15)

Re-construction of Roman Arch, ancient Rimini gate

Bed **J**oint **R**evitalising

cFRM carbon Fiber Reinforced Matrix

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON *SOME* PIONEERING EPISODES

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: a look on some pioneering events

RE-CONSTRUCTION

NOTO (SICILIA, ITALIA) CATHEDRAL

Reconstruction 1996-2007 of collapsed parts of Noto Cathedral (Sicilia, Italia) utilized

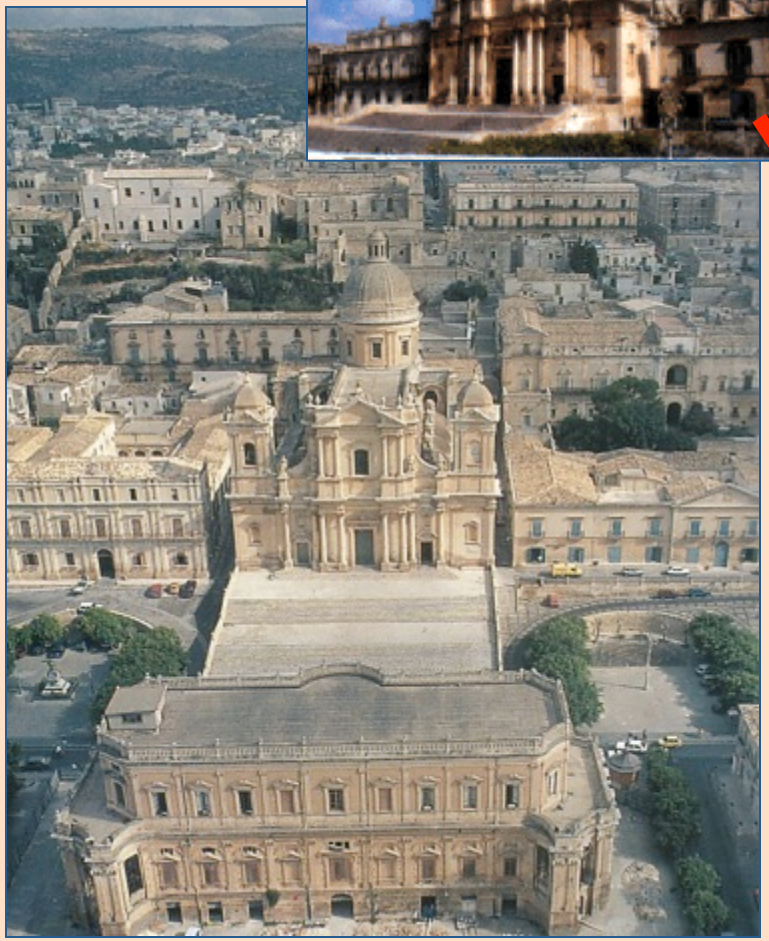
1) *plating* of arches covering principal nave

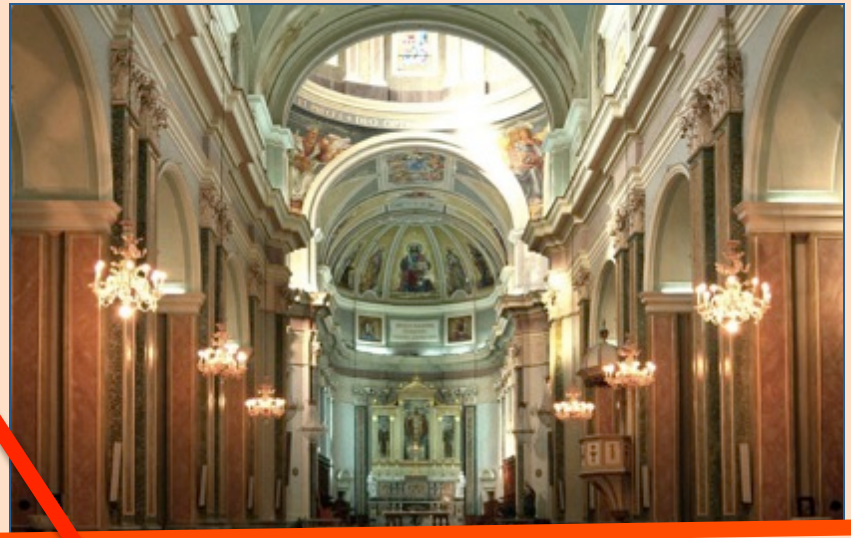
and

2) *bed joints re-vitalising*

with cFRCM in both applications.

before





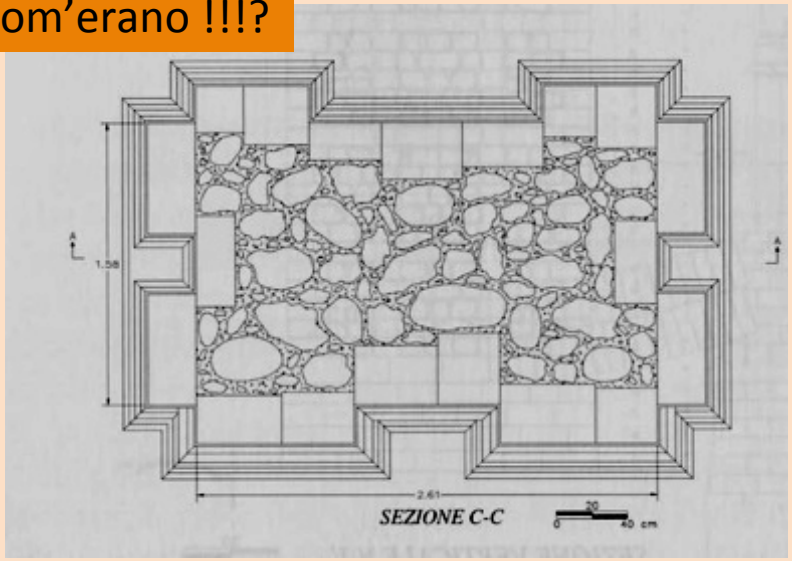
after

NOTO 1996

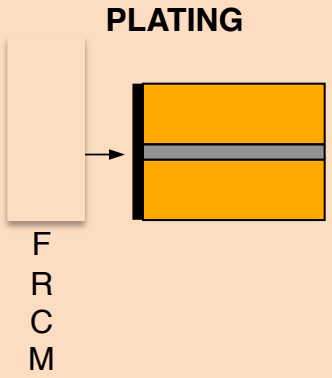
If it is possible to built ***where it was***, I do not think is possible to built ***as it was***.

“Se è possibile costruire *dov’era,*
non credo sia possibile costruire
com’era”
ALDO ROSSI

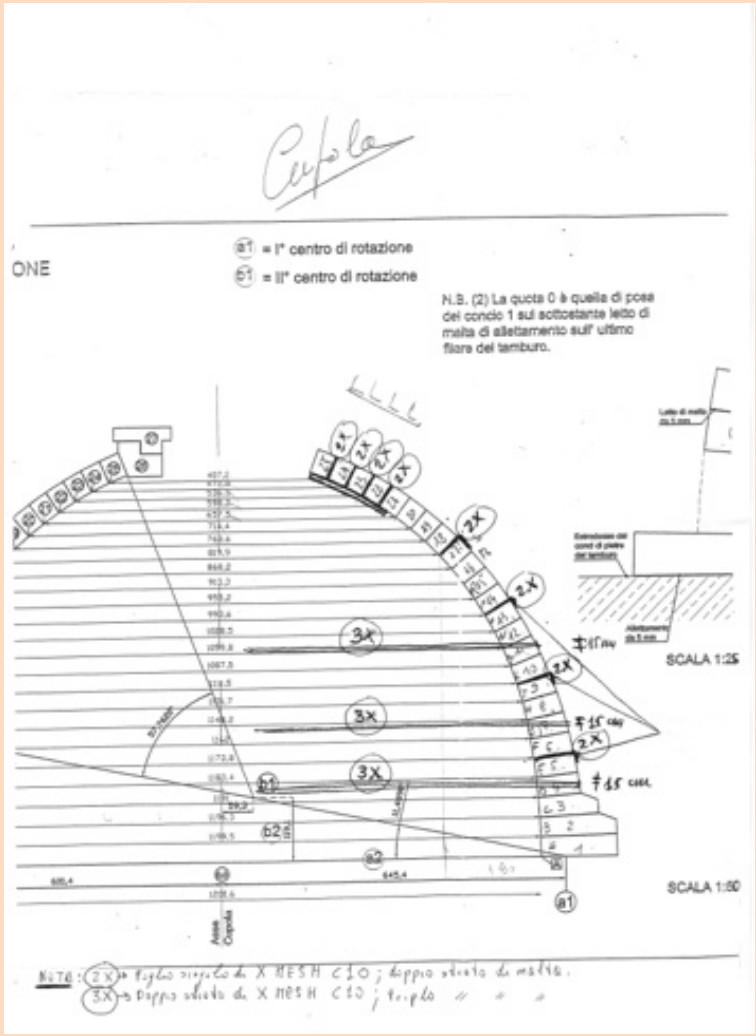
Colonne com’erano !!!?

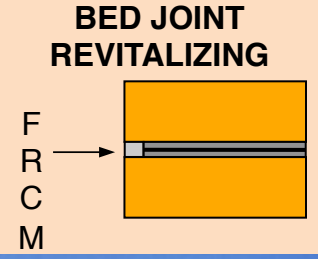


Re-construction of collapsed Noto Cathedral (Sicilia, Italia) utilized *plating* of arches covering principal nave



Re-construction of collapsed Noto Cathedral (Sicilia, Italia) utilized *bed joints re-vitalising* with cFRCM in both applications..

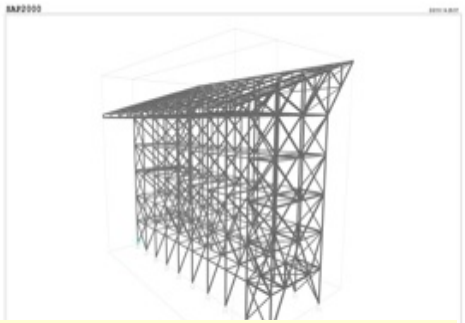




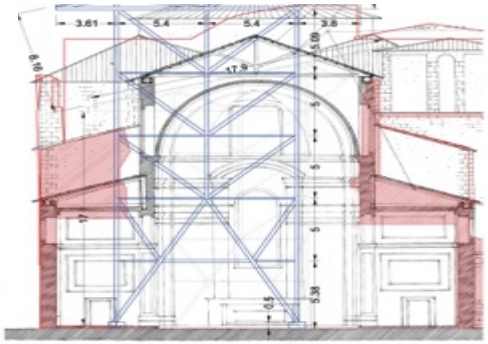
Chiesa di s. Maria di Paganica AQ

g F R P

Idea and project:
Ing L. Marchetti - Prof S. Russo



Protective Structure



Reticulated Frame with Composite gFRP Prophiles

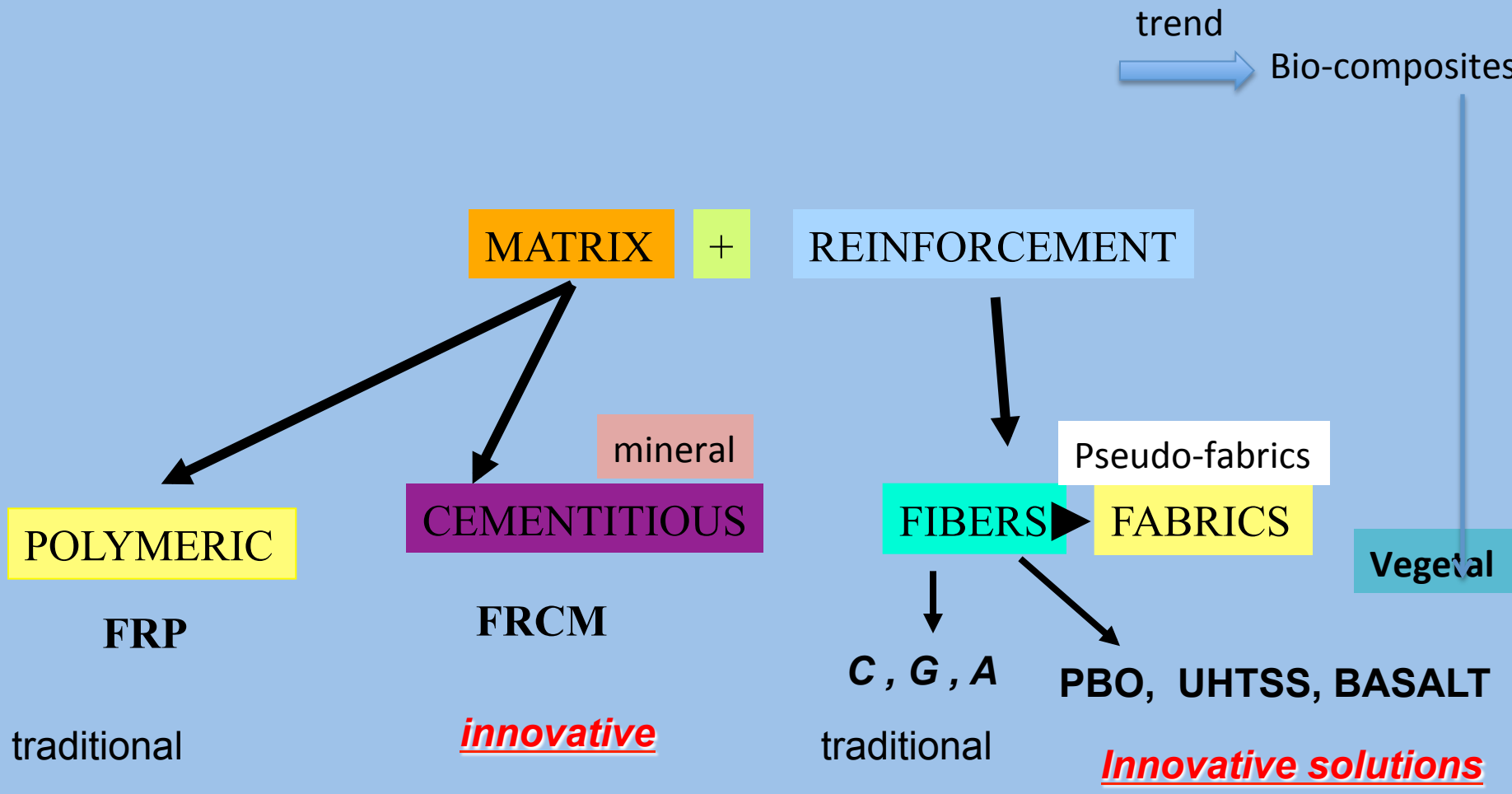
Idea and project:
Ing. Luciano Marchetti e Prof. Salvatore Russo (con Ing. A. Adilardi e Arch.G. Boscato)

TIPOLOGIE DI COMPOSITI ADATTI PER RINFORZARE LE COSTRUZIONI STORICHE

Fiber Reinforced Polymer **FRP**
Fiber Reinforced Cementitious Matrix **FRCM**
Textile Reinforced Mortar **TRM**
Steel Reinforced Grout **SRG**

Composites as mechanism inhibitors

COMPOSITE MATERIAL



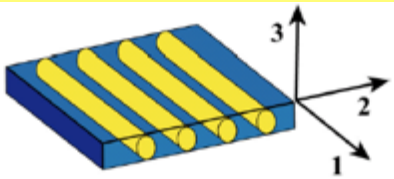
COMPOSITE

REINFORCEMENT of composite

continuous

FIBERS

- **STEEL** — METALLIC
- **CARBON**, **GLASS**, **BASALT** — INORGANIC / MINERAL
- **ARAMID**, **PBO, PVA ..**, **FLAX** — ORGANIC / VEGETAL



MONO-DIRECTIONAL

Pseudo-TESSUTO

Pseudo FABRIC

BI-DIRECTIONAL

Trama e ordito TESSUTO

weft and warp FABRIC

MULTI-DIRECTIONAL

PBO Fibers

Poliparafenilen-Benzo-bisOxazolo (PBO)

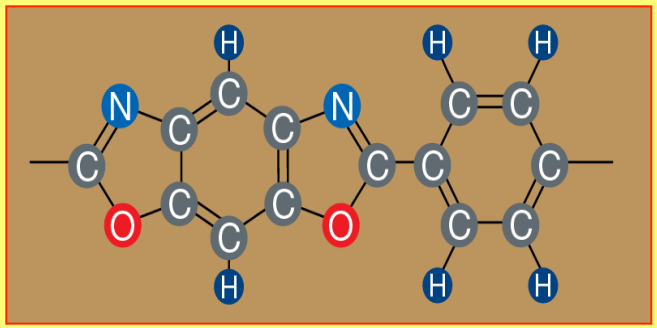
Developed by TOYOBO Co. Japan named Pbo Zylon® .

thoughness, high modulus, resistance to abrasion, fire, UVA

better than Aramidic fibers. Low humidity absorbtion (0.6%).

MATERIAL	DENSITY [kg/m³]	ELASTIC MODULUS [GPa]	TENSILE STRENGTH [MPa]	RUPTURE ELONGATION [%]	CRITIC TEMPERATURE [°C]
PBO	1560	270	5800	2.15	650

SINTETIC
Co-valent Link with cement matrix

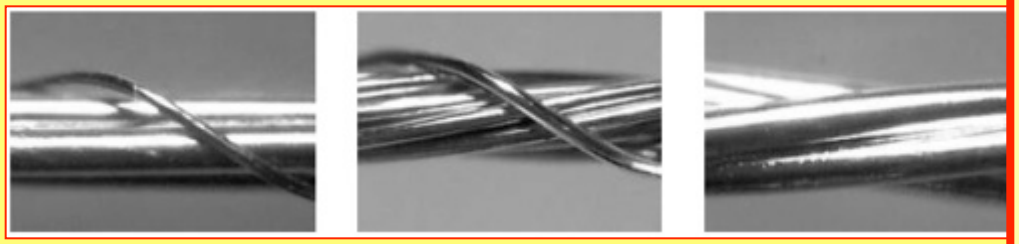


STEEL wires

Initials: UHTSS acronym : *Ultra High Tensile Strength Steel*

small wires assembled with torsion arranged in fabrics.

STEEL YARN ?



Composites

SRG (Steel Reinforced Cement-Grout)

SRP (Steel reinforced Polymer)

patented by HARDWIRE,

Reinforcement GOODYEAR used for pneus

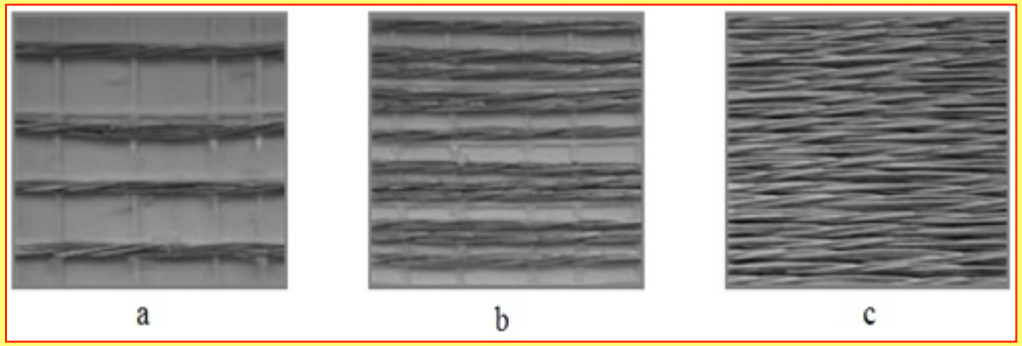
Pseudo-fabrics (mono-directional):

a) Low (4 trefoli / inch);

b) Medium (12 trefoli / inch);

c) High (23 trefoli / inch)

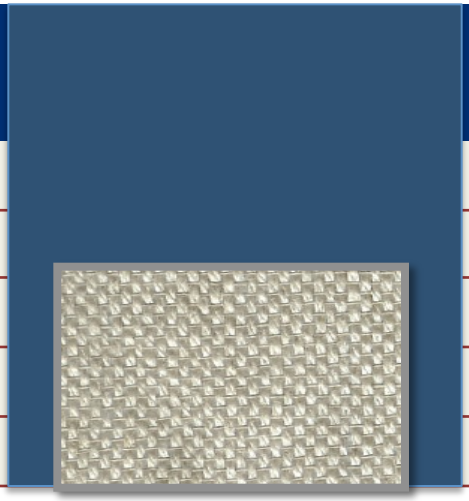
Steel fabrics



bio-composites,

Lino=FLAX Canapa=HEMP Juta=JUTE

Fibra	Densità (g/cm3)	Carico rottura (MPa)	Costo relativo (dollari /kg)
carbonio	1,8	1700-2400	220
vetro	2,5	1400-2500	5
lino	1,5	900-1200	1.5
canapa	1,4	400-700	1.3
juta	1,4	400-600	0.3



mineral-composite
basalt fibres

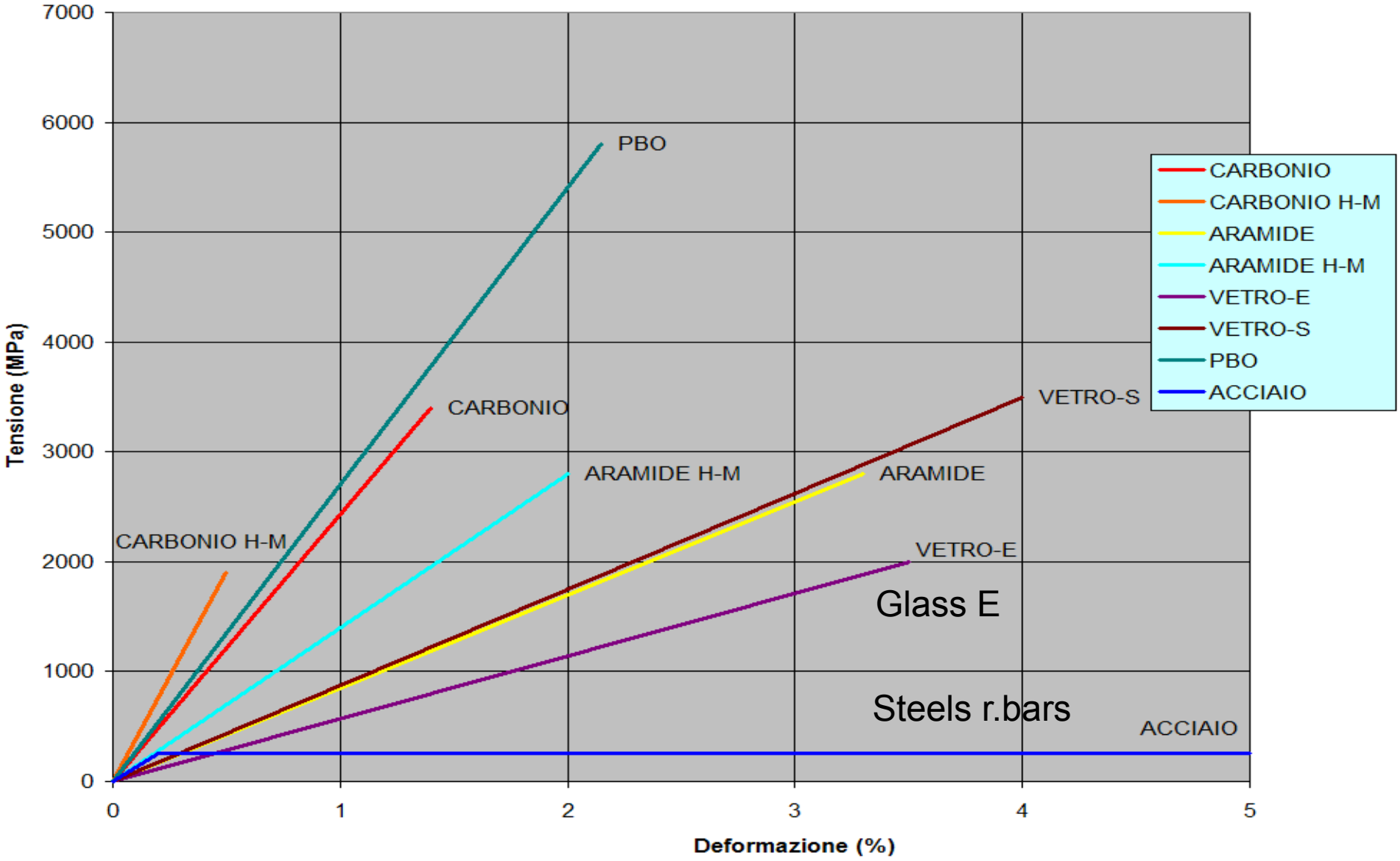
- Thermal and acoustic insulating
- Stable at high temperature (ideal for FRCM).
- Chemical resistant in aggressive ambient.

bFRCM

Mineral matrix + basalt fabrics for masonry strengthening !!!

Fibra	Conduttività termica (w/m k)	Temperatura fusione (°C)	Resistenza trazione (Mpa)	Moludo elastico (Gpa)
Vetro	0.034-0.04	1120°	3450	77
Basalto	0.031-0.038	1450°	4840	89

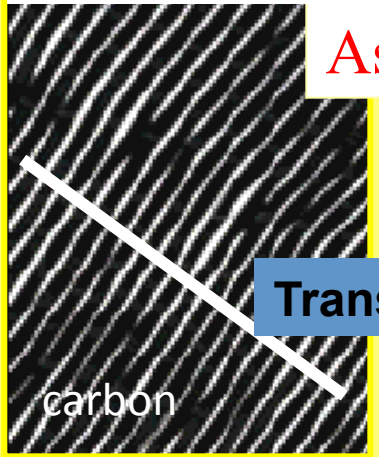
Fibers COMPARISON 2



Pseudo-fabric, mono-directional

Same direction

Assembled yarns or rovings

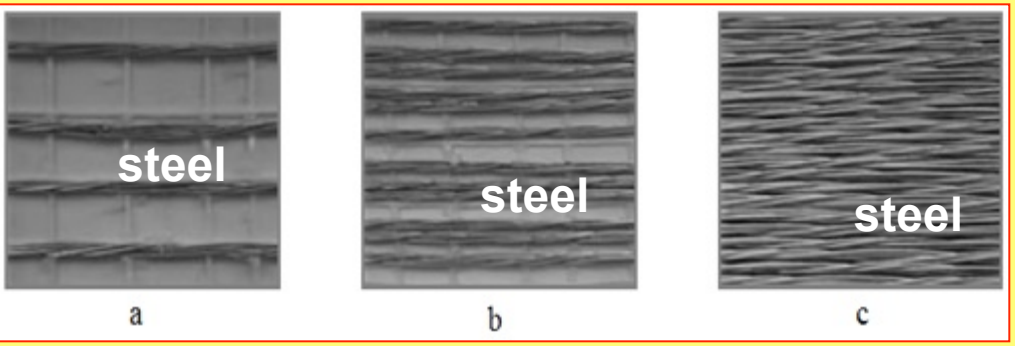


multi-directional

ASSEMBLED ROVINGS

Pseudo-fabric, bi-directional

Mesh /Grid/

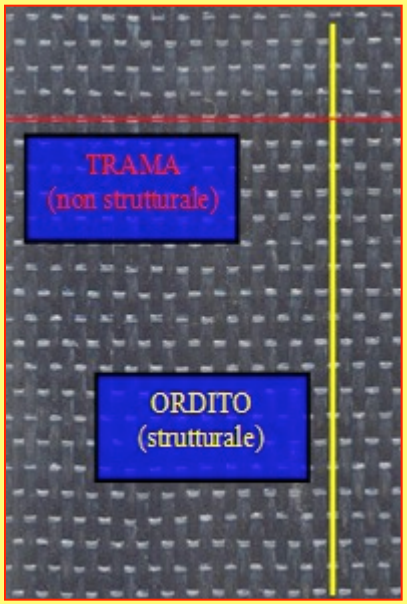


FABRICS (textiles)

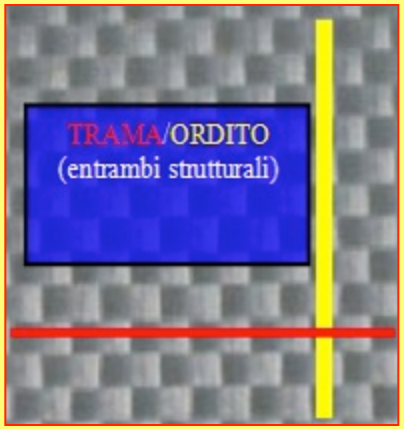
Trama = weft TRAMA (engl. WEFT, franch. TRAME, spanish TRAMA).

ORDITO (engl. WARP, french CHAINE,,spanish URDIMBRE)

Ordito = warp Set of longitudinal yarns in which the transversal wires are inserted



MONO-DIRECTIONAL



weft and warp

Bi-directional

Multi-Axial

MATRIX of composite

CEMENT BASED (GROUT)

FRCM Fiber Reinforced Cementitious Matrix

POLYMERIC (RESIN)

FRP Fiber Reinforced Polymer

A and B components of epoxy resin

MATRIX PREPARATION

Hand-process

In Lab

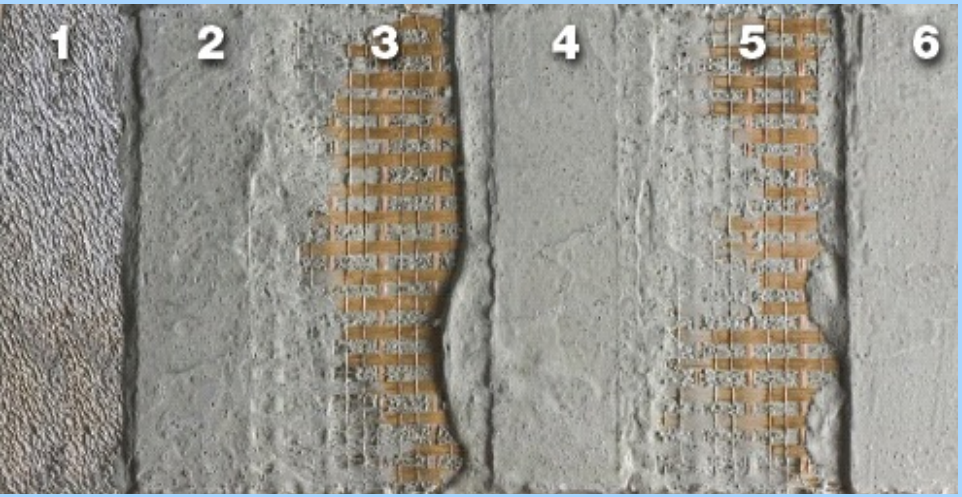
In -situ

Impregnation of fabric

COMPOSITE FRCM

MATRIX (CEMENT BASED)

FRCM



1. SUPPORT MATERIAL
2. FIRST LAYER OF MATRIX
3. MESH OF FIBER (pboFRCM)
4. SECOND LAYER OF MATRIX
5. SECOND MESH OF FIBER (opzionale)
6. THIRD LAYER OF MATRIX

COLLASSO DEL COMPOSITO

MECCANISMI PECULIARI DI CRISI

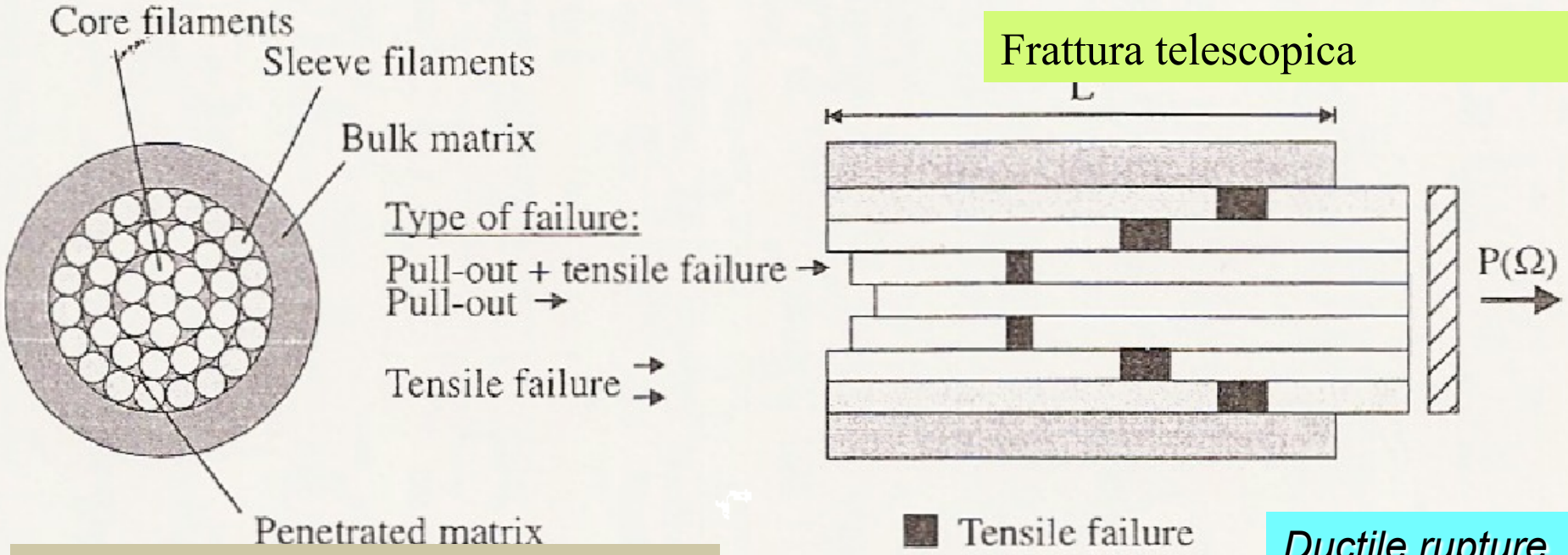
Dipendenti da natura della matrice e delle fibre e dall'accoppiamento

FRCM: Meccanismo di collasso

TEST: **PULL OUT of *ROVING***

Adesione dei filamenti esterni del roving alla matrice:
C moderata PBO forte

I filamenti interni al roving rimangono asciutti e durante il collasso cedono ed esibiscono dissipazione energetica per attito



Frattura telescopica

German Research Group Representation

Ductile rupture

Materiale del supporto + FRCM

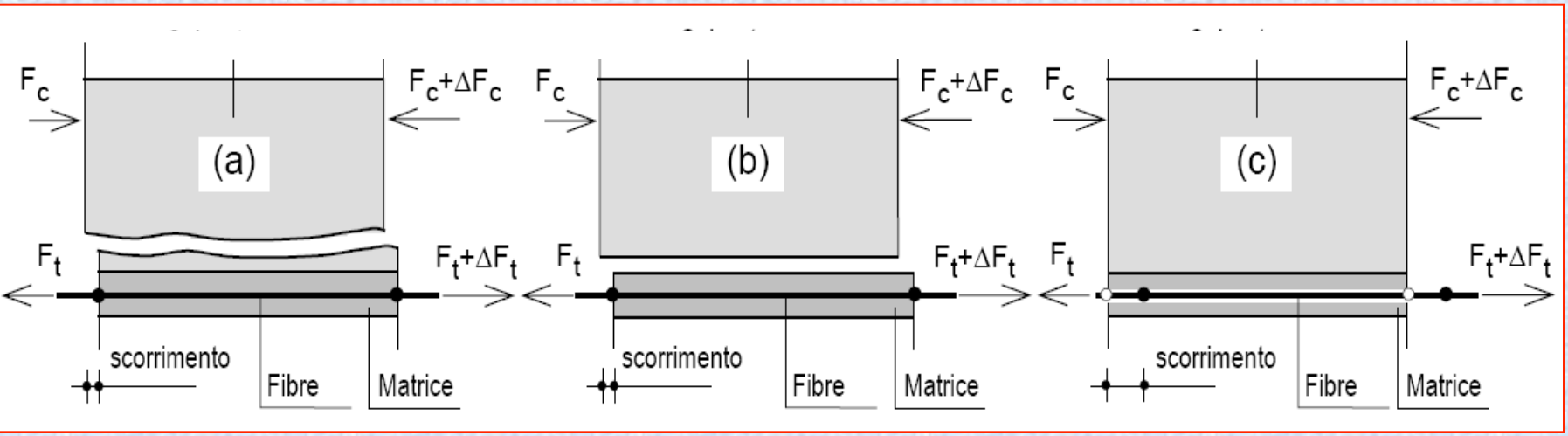
Meccanica del collasso

ASPETTI GENERALI

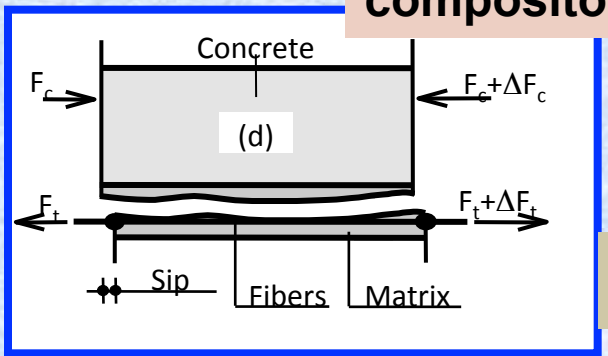
Delaminazione Nel supporto

Distacco alla interfaccia

Scorrimento delle fibre

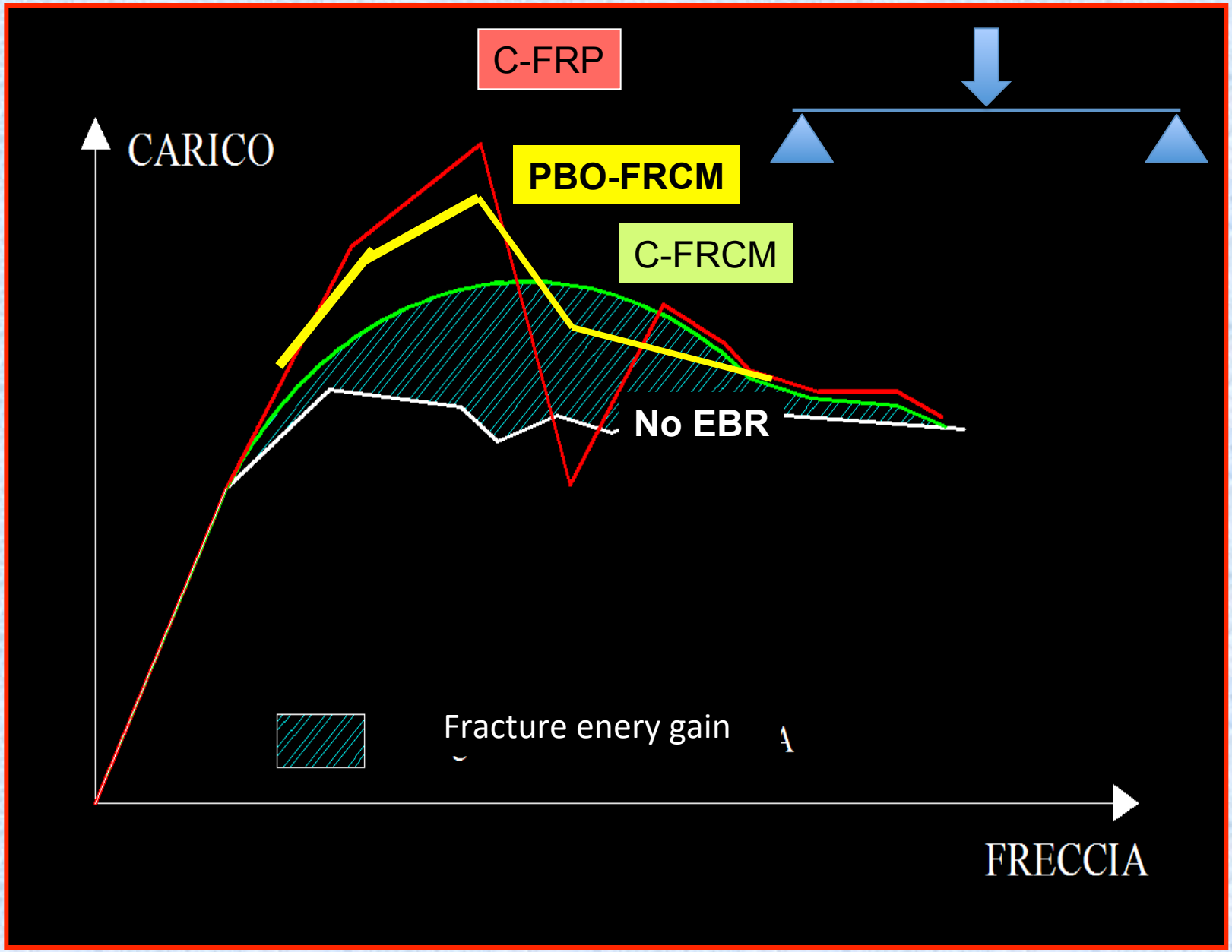


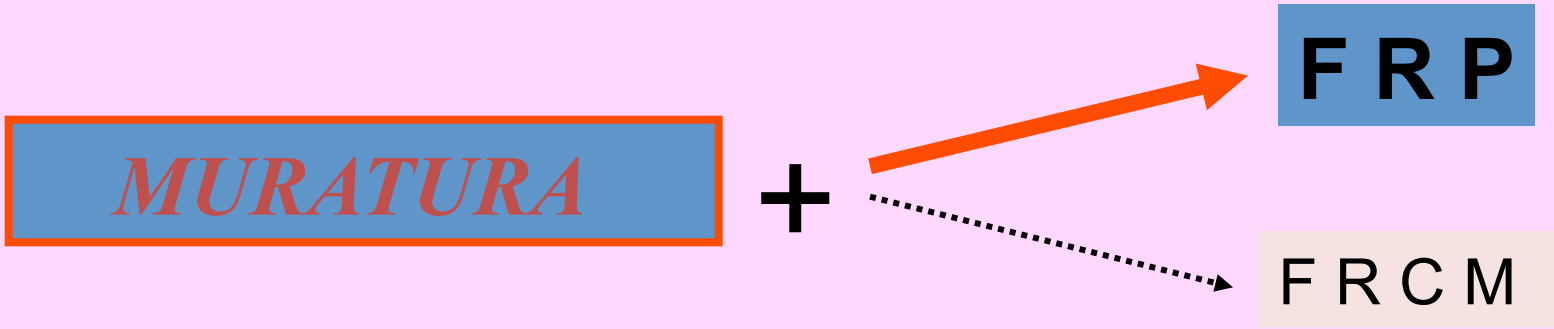
Delaminazione Nel pacchetto composito



Representation from F. Focacci et al.

(a) + (b)


C-FRP
CARICO
PBO-FRCM
C-FRCM
No EBR
Fracture enery gain
FRECCIA

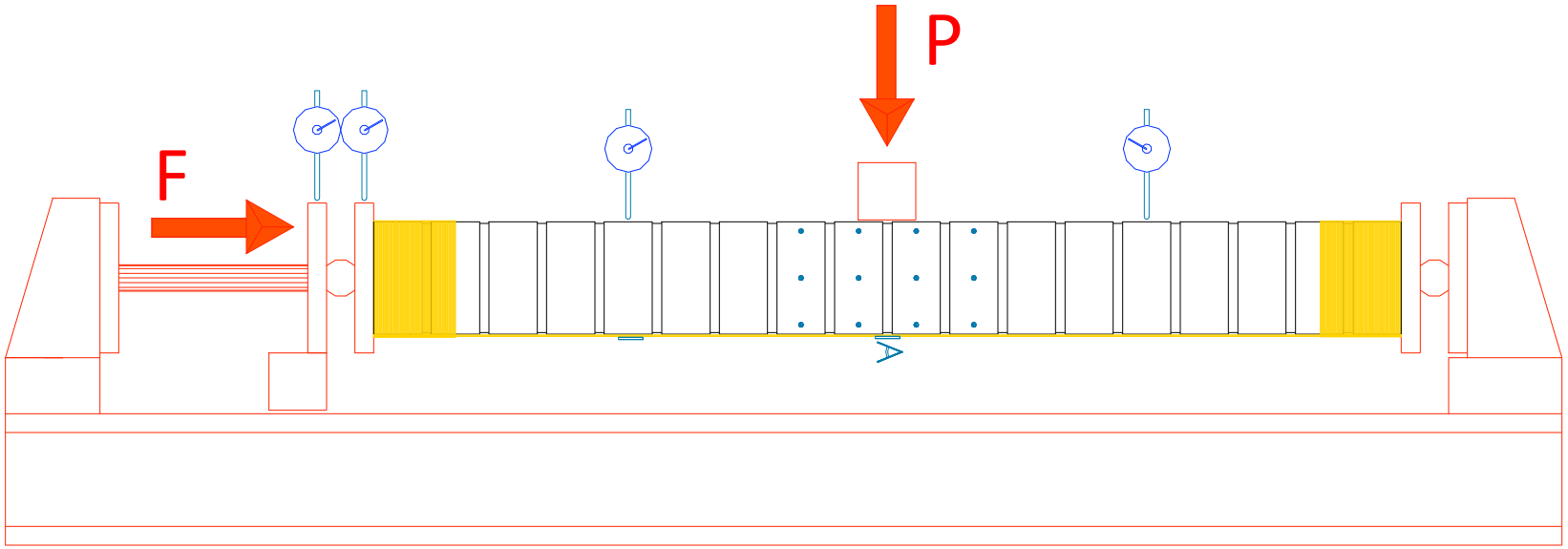


Some Experimental tests at IUAV UNIVERSITY of VENICE

FRP

1. MACRO-ELEMENT BEAM-COLUMN

SIMULATION OF WALL SUBJESTED TO AXIAL PERMANENT LOAD AND TRANSVERSAL VARIABLE LOADING P



DEFLECTION GAUGE

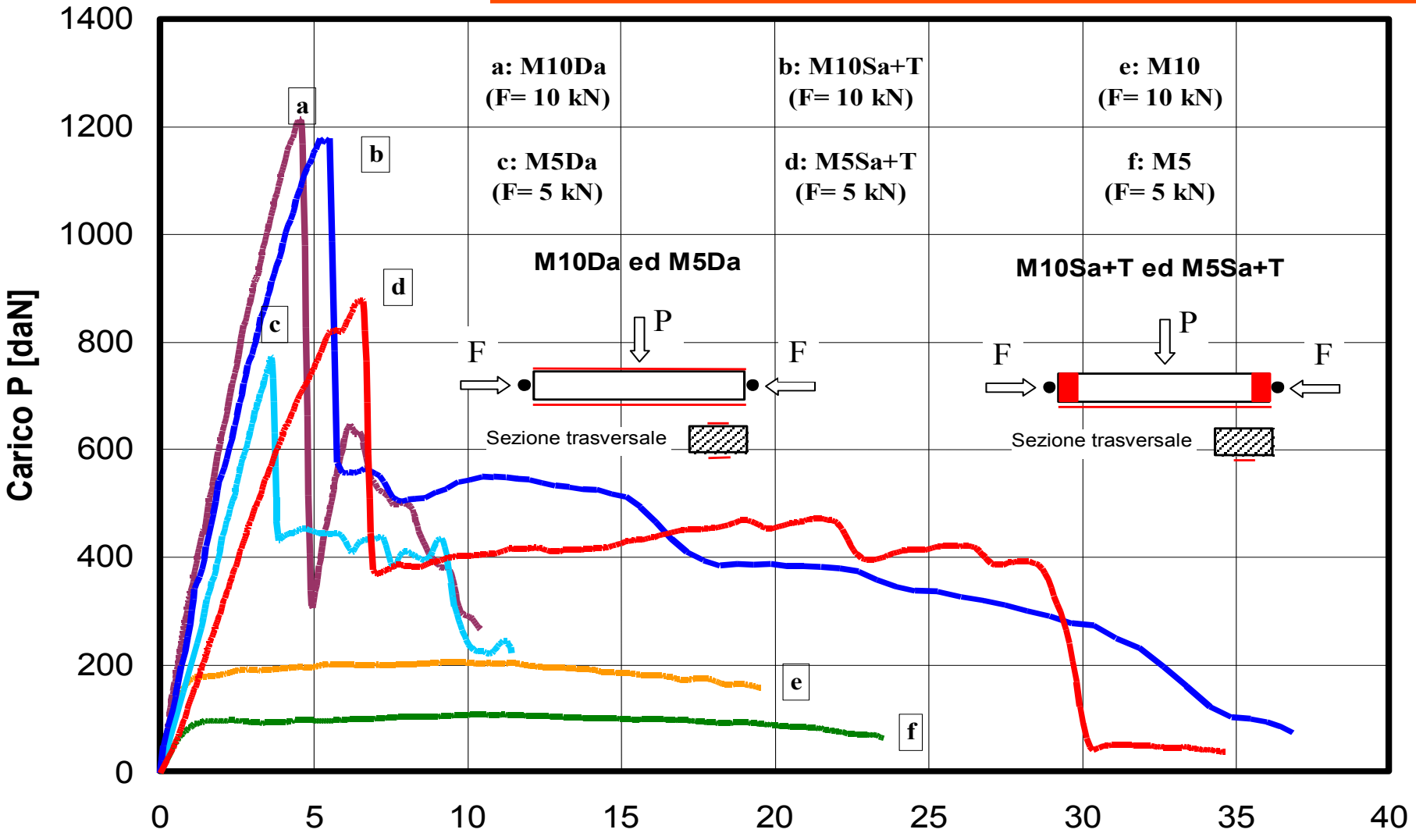
ELETRIC STRAIN GAUGE

MECHANICAL STRAIN GAUGE

OPTIC FIBER SENSOR

CROSS SECTION

I° investigation

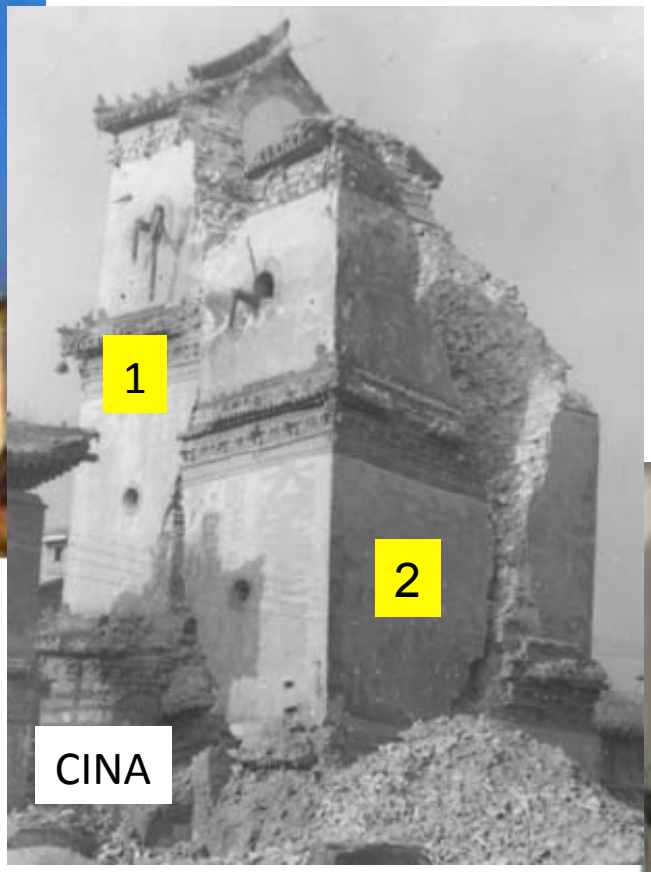


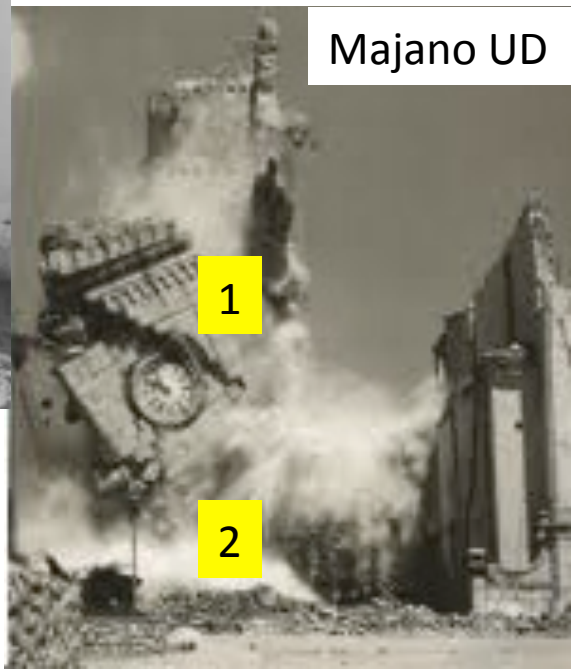
MURATURA

MECCANICA DEL COLLASSO

PRINCIPI DI BASE

OBIETTIVO: “RItardare” o “INIBIRE” il meccanismo di collasso durante azioni eccezionalmente severe non modificando i meccanismi resistenti in condizioni ordinarie di servizio ossia rispettando il funzionamento statico di progetto.





COLLASSO DI TORRI:
MECCANISMI

Strutture di muratura
Terremoto

Il meccanismo di collasso divide la struttura di muratura compatta (solida e robusta) in BLOCCHI RIGIDI integri

S. GIULIANO DI PUGLIA (CB Italia) 2002

Pietra

La muratura a doppia foglia (senza diatoni) Manifesta DE-FOLIAZIONE

ABRUZZO 2009

EMILIA 2012

Solid and robust masonry

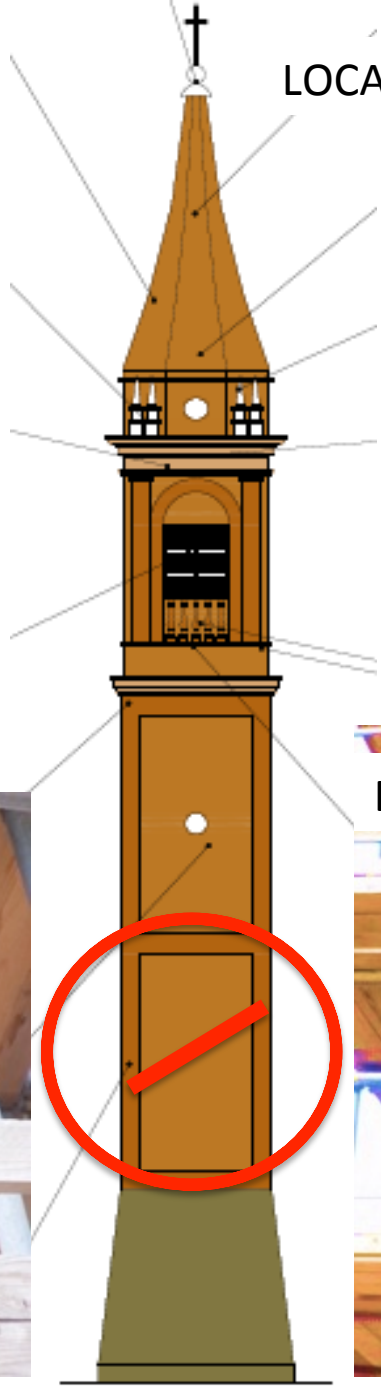
Mattone

BAGNOLO IN PIANO (RE Italia) 1996

DISLOCATION A

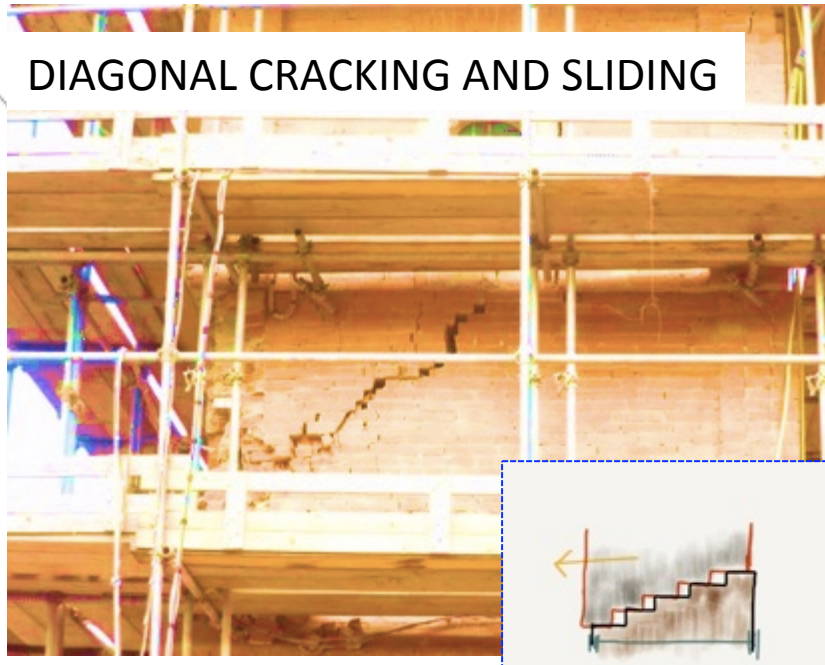
LOCAL DAMAGE BY KEY OF INTERN. TIE-ROD

RENO CENTESE (CENTO)



DISLOCATION B

DIAGONAL CRACKING AND SLIDING



CAVEZZO

MECCANISMO TIPICO

RIDUZIONE IN BLOCCHI

INTERNAMENTE INTEGRI

CONTRASTO NEL PIANO DI VIBRAZIONE

Compound resulting from inorganic process (of nature)

Mineral-composites,

Culture and technicality

Demolition (partial)
Chimney in Bologna

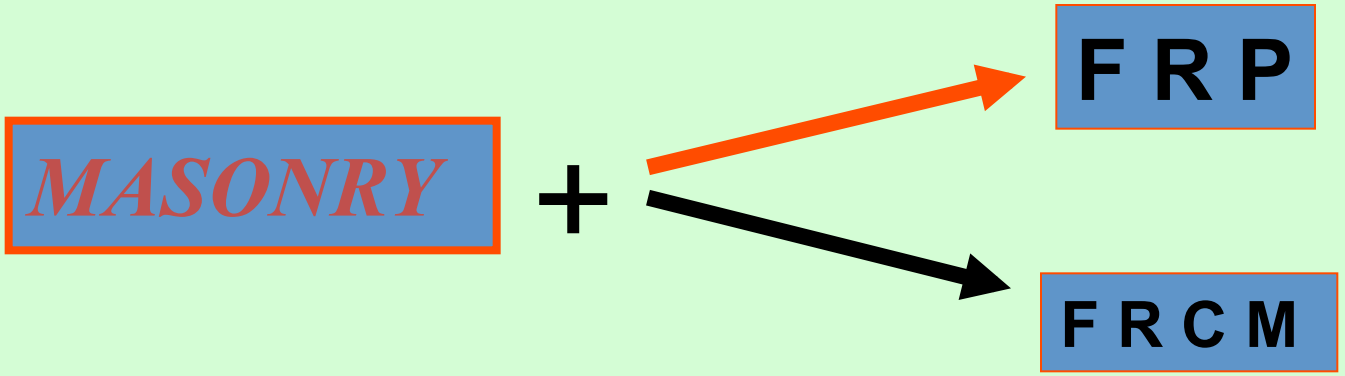
Demolition (partial)
Chimney in Ferrara
Faculty of Eng

ITALIAN
Negative history

EMBALMED ARCHITECTURE !!!

cFRCM

chimney
Sawmill CUNY
Gerardmer, France.
Wrapping for
strenghtening



BASIC PRICIPLES and EXPERIMENTS

OBIETTIVO: “RItardare” o “INIBIRE” il meccanismo di collasso durante azioni eccezionalmente severe non modificando i meccanismi resistenti in condizioni ordinarie di servizio ossia rispettando il funzionamento statico di progetto.

Intervention to reduce vulnerability by means the contrast of collapse mechanisms

"Principia"

"Vincula"

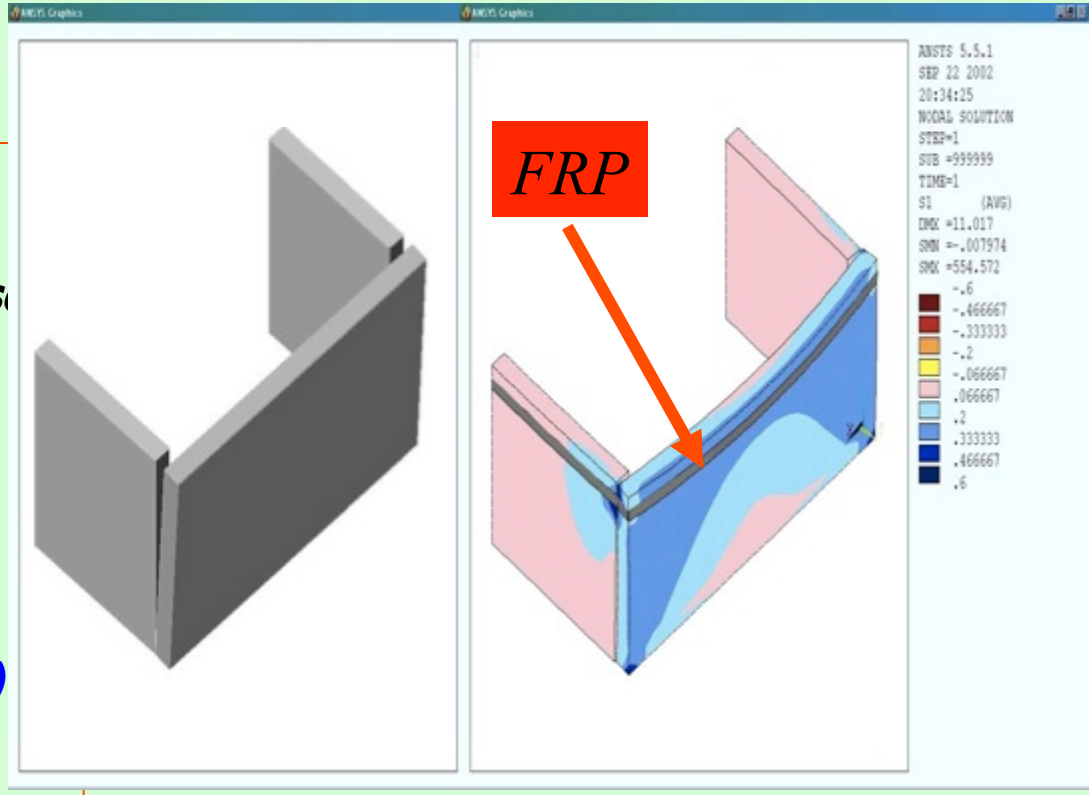
CONSTRAINS

to mechanisms of seismic collaps

"Auxilia"

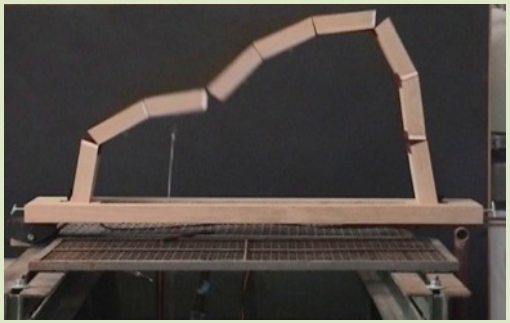
AID for resisting to seísmic actions;

no STRUCTURAL change for frequent loadings (verticals)



ARCH (AND VAULTS) STRENGTHENING

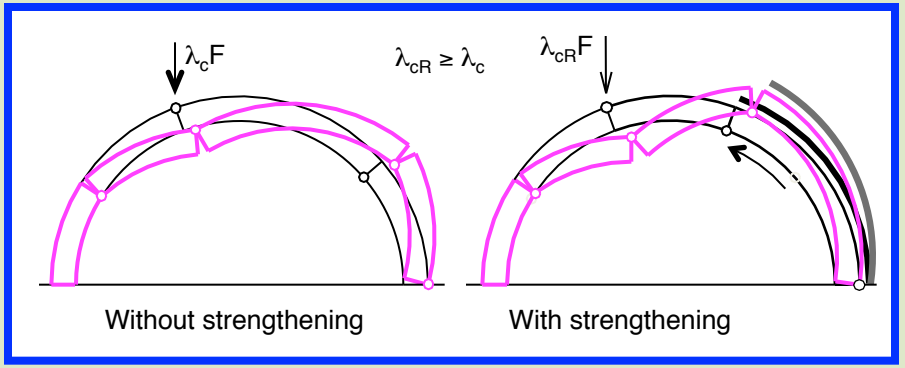
Mode I (opening)

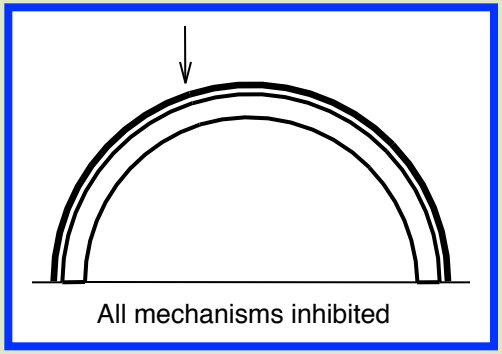


Alternate hinges
- Two at intrados
- Two at extrados

STRENGTHENING STRATEGY”

- **External strengthening (FRP o FRCM) bonded to intradoss or to extradoss**
  - **partial: c**ollapse with mechanism
  - **Total**: (collapse for presso-flexure or shear)





SHEAR

- **WITHOUT STRENGTHENING**

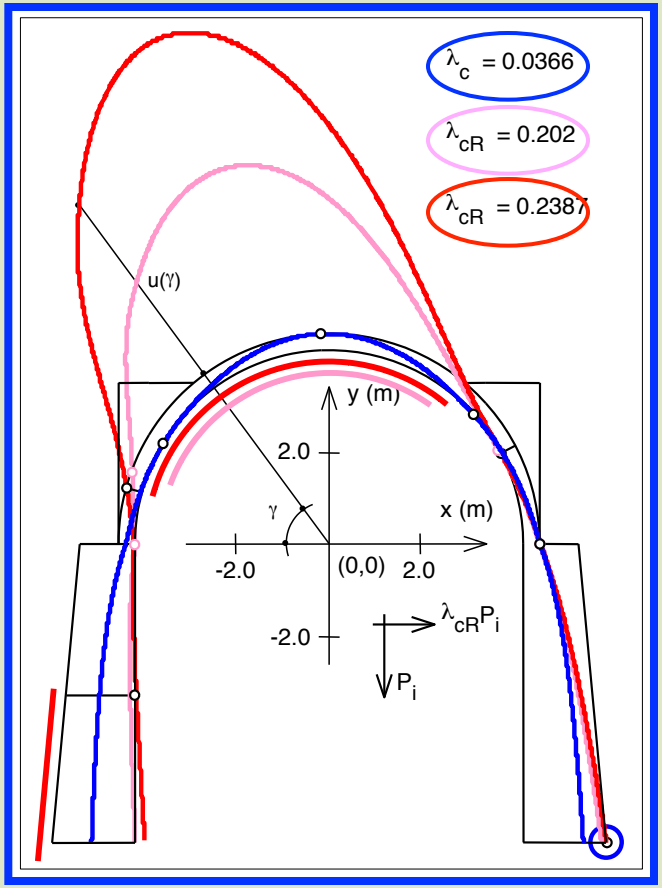
  ➡ SHEAR collapse very rare (thrust line approximatly parallel to middle line)

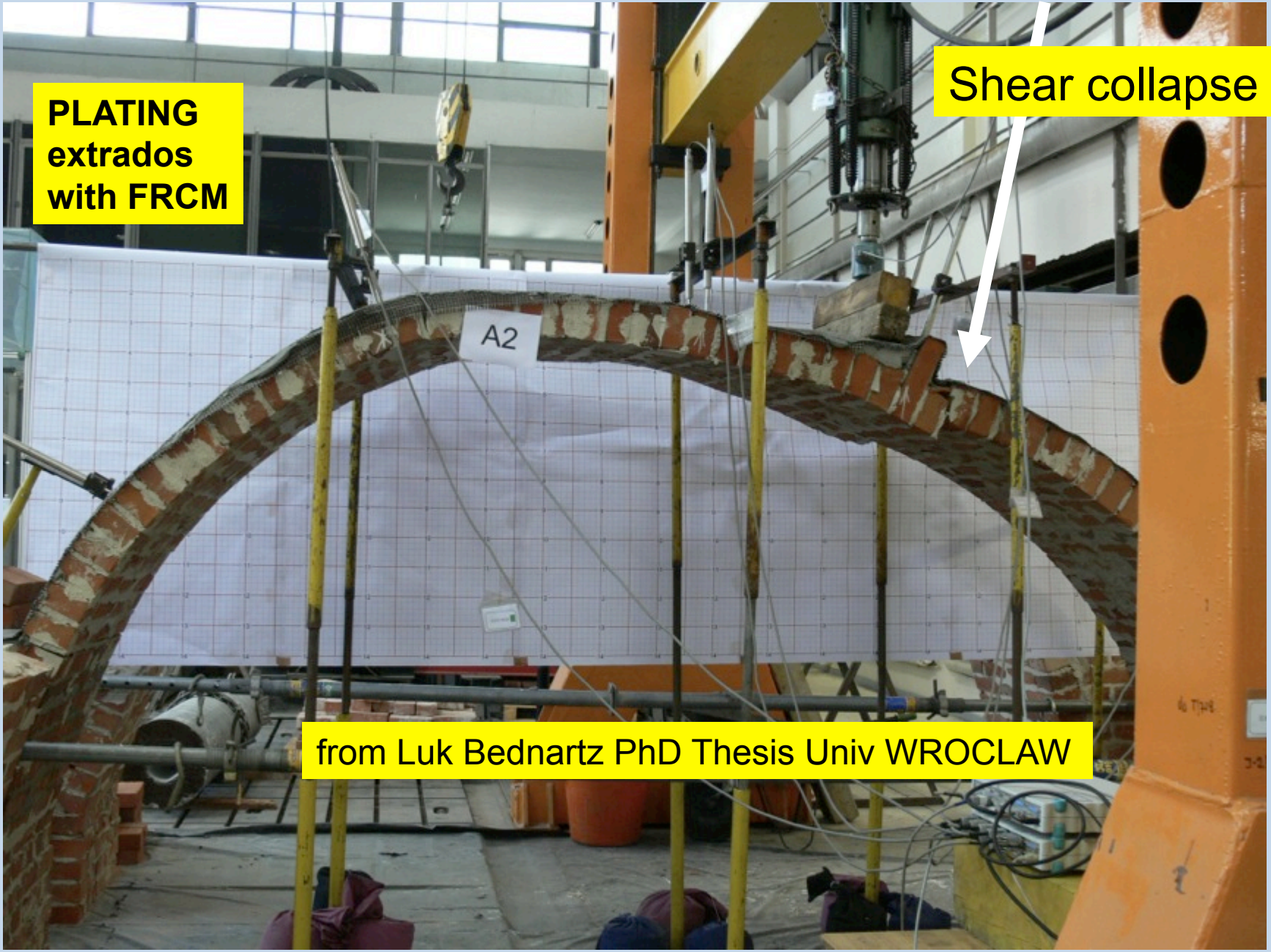
- **WITH STRENGTHENING**

  ➡ Before the hinge collapse mechanism can appear the shear detachment (sliding joints)

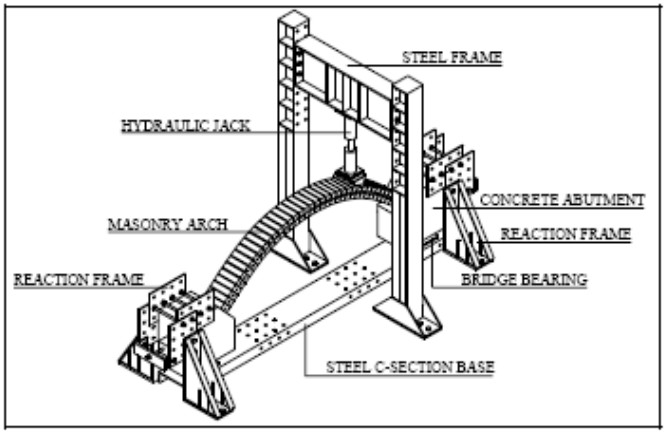
  Thrust line very inclined respect middle line.

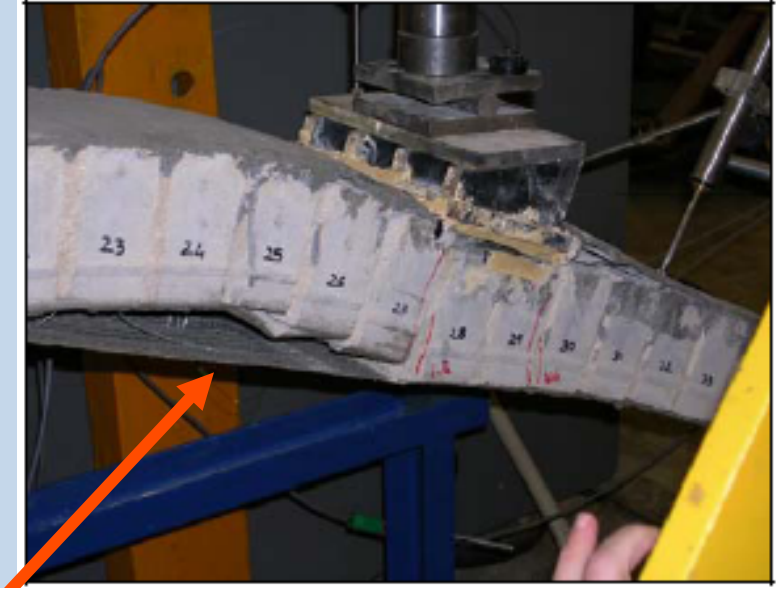
Experiments of Bednartz FRCM strengthening

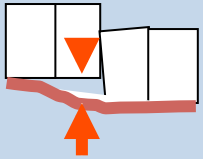



PLATING
extrados
with FRCM
Shear collapse
A2
from Luk Bednartz PhD Thesis Univ WROCLAW

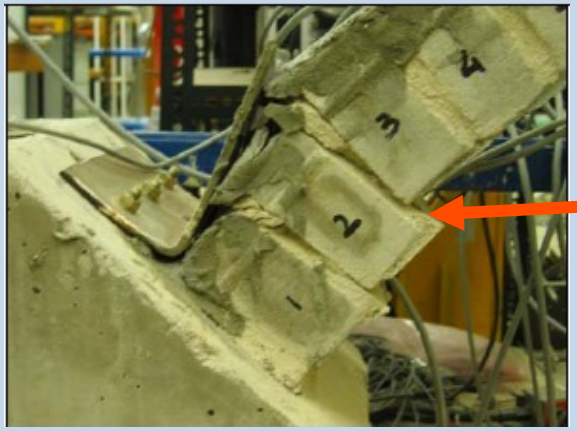
Steel-FRCM







Steel net



Shear sliding

debonding

From A. BORRI University of Perugia (Italia) et al. 2006

COMPORTAMENTO SISMICO DELLE CHIESE

ANALISI STORICA DEL DANNO SISMICO

➡ **IN COERENZA CON L'APPROCCIO PER MACROELEMENTI**

PER STRUTTURE DI MURATURA COMPATTA

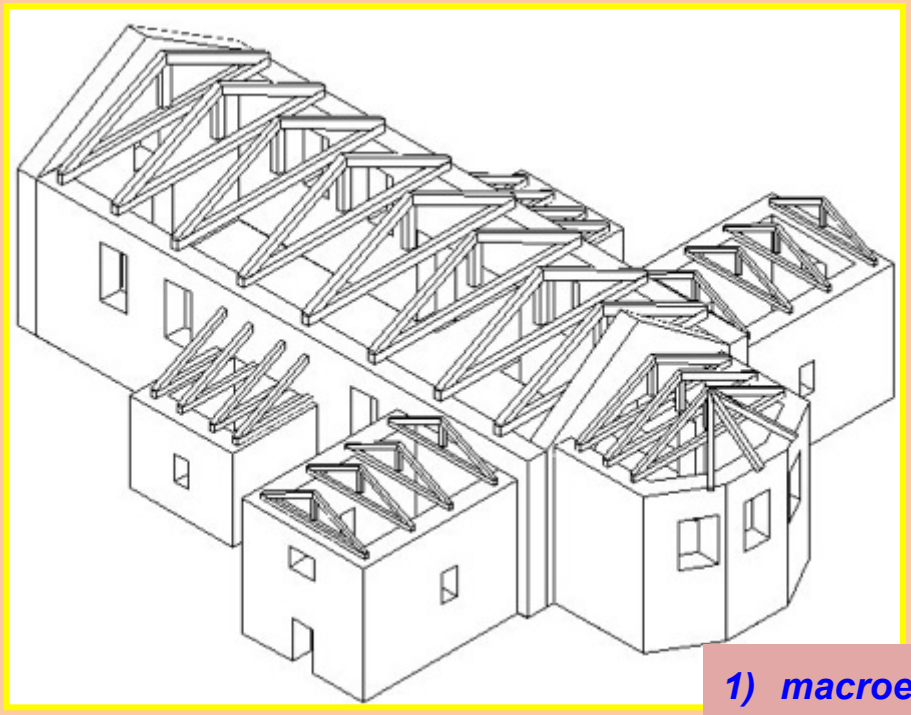
CONSIDERAZIONE CON ESCLUSIONE DELLE MURATURE A FOGLIA MULTIPLA{ **Multiple-leaf}**
(cioè A SACCO E A DOPPIA PARETE SENZA DIATONI)

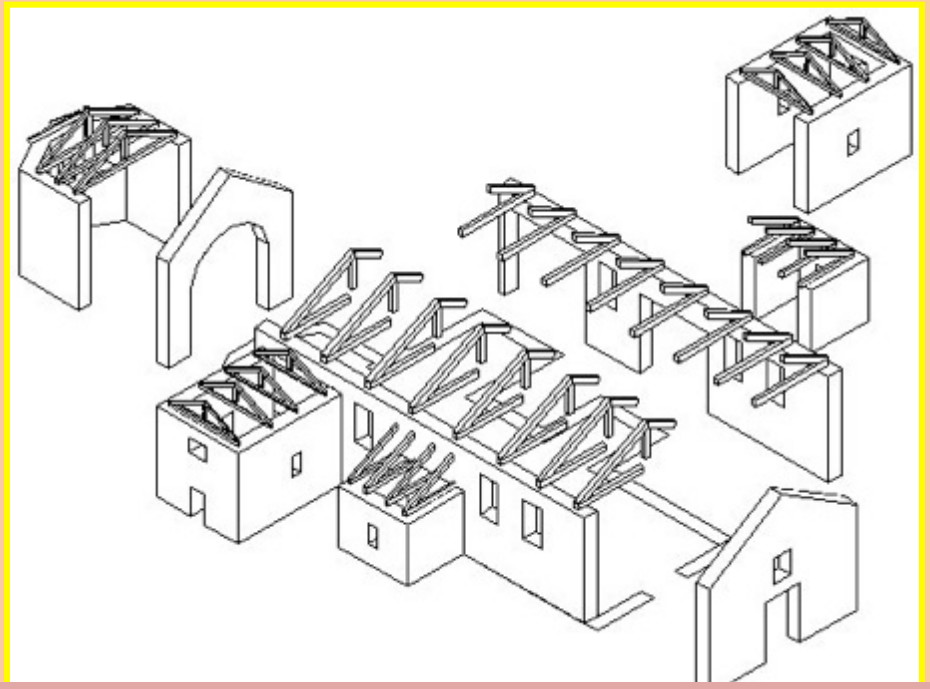
Molise 2002

Abruzzo 2009

Defoliation of masonry

BUILDING ⇨ ***Structural macroelements (architectonically and structural defined) which have peculiar and recurrent seismic behaviours and their aggregation***





COLLAPSE MECHANISMS OF THE BUILDING ⇨

1) macroelement mechanisms

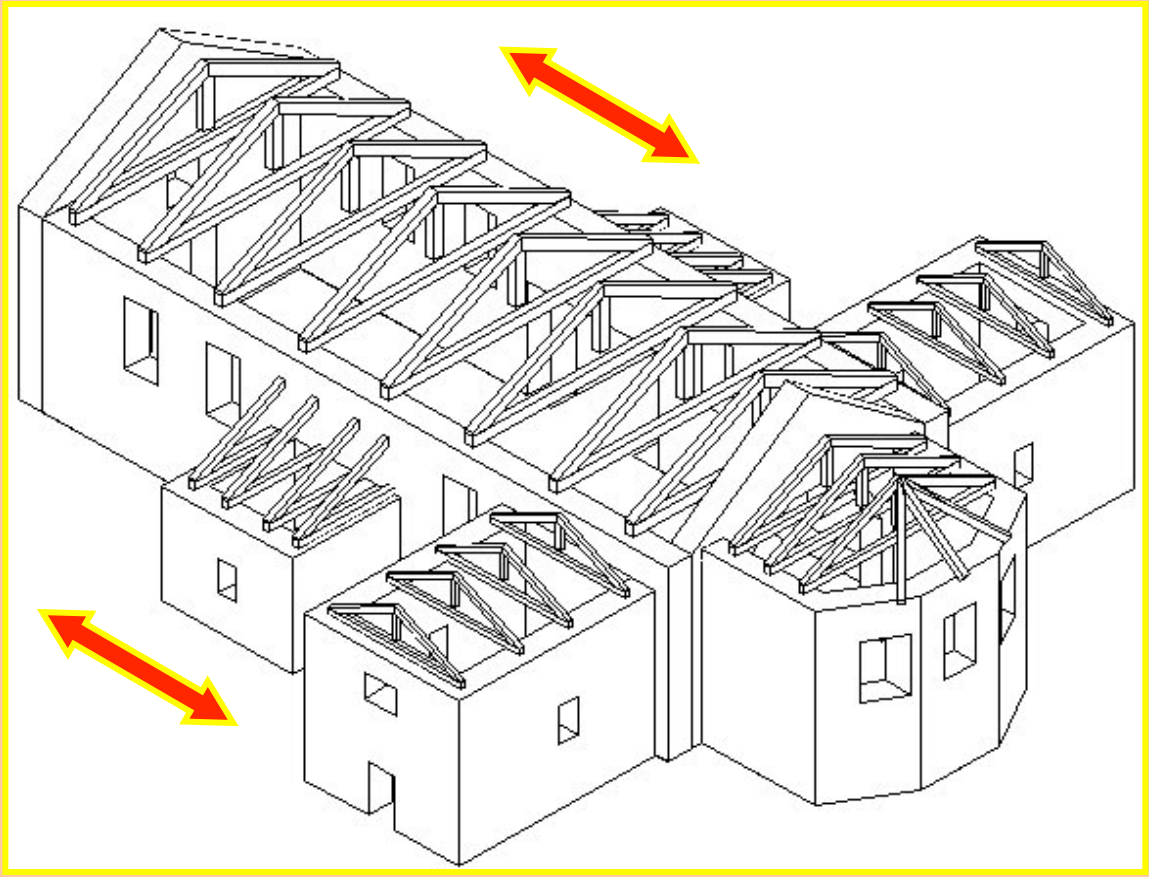
+ o -

2) disagregation mechanisms of macroelement each other

The aggregation lines are not only geometric lines, but they represent the transmission lines of stresses.

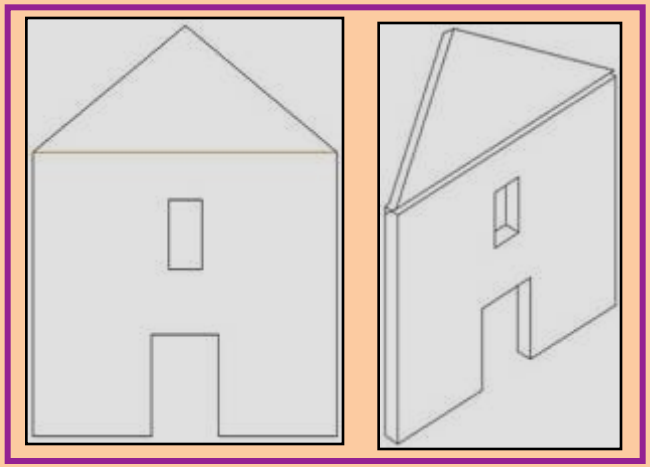
So, they can be considered <u>structural lines</u>, being fundamental to the definition of the building behaviour.

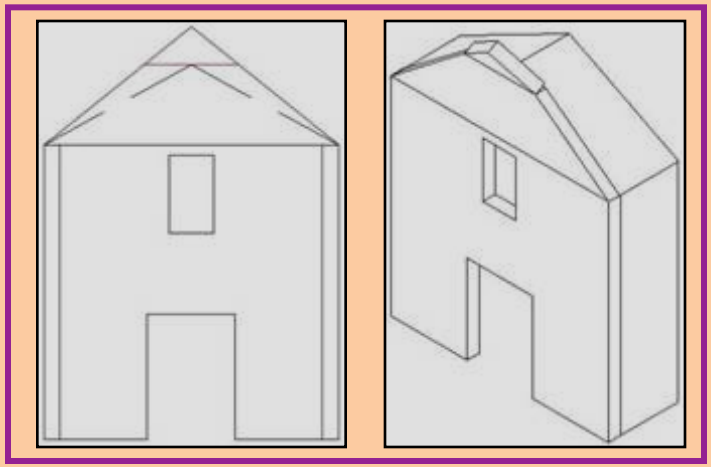
DOMINANT SEISMIC DIRECTION ⇨ **LONGITUDINAL**



DOMINANT SEISMIC DIRECTION ⇨ **LONGITUDINAL**

Macroelement: façade





Umbria 1997

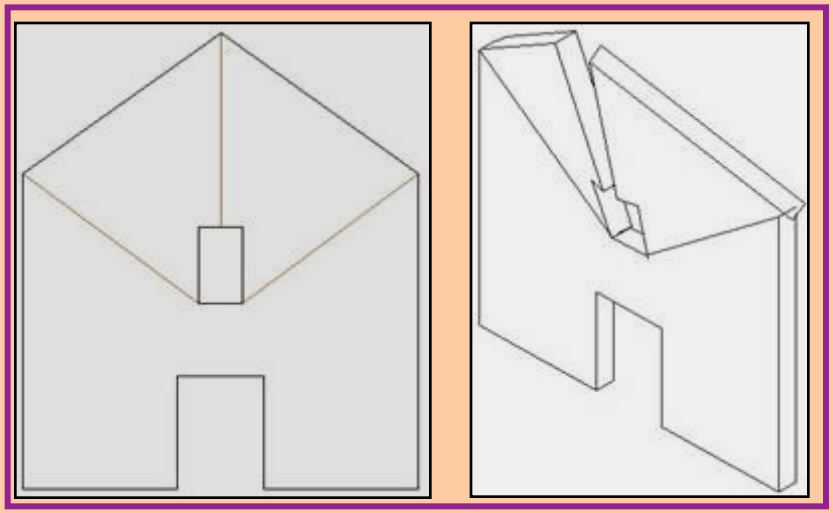
Umbria 1997

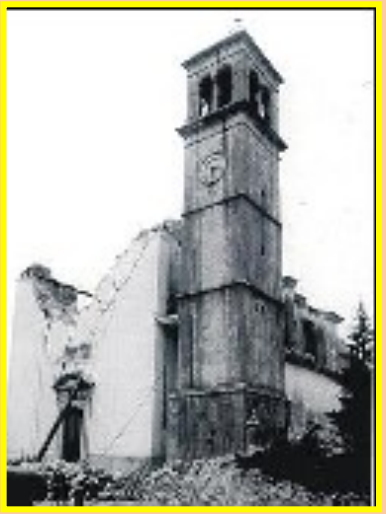
Molise 2002

Lombardia 2004

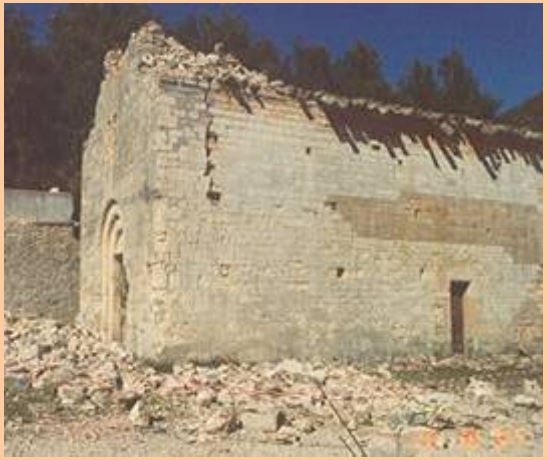
DOMINANT SEISMIC DIRECTION ⇨ **LONGITUDINAL**

Macroelement: façade





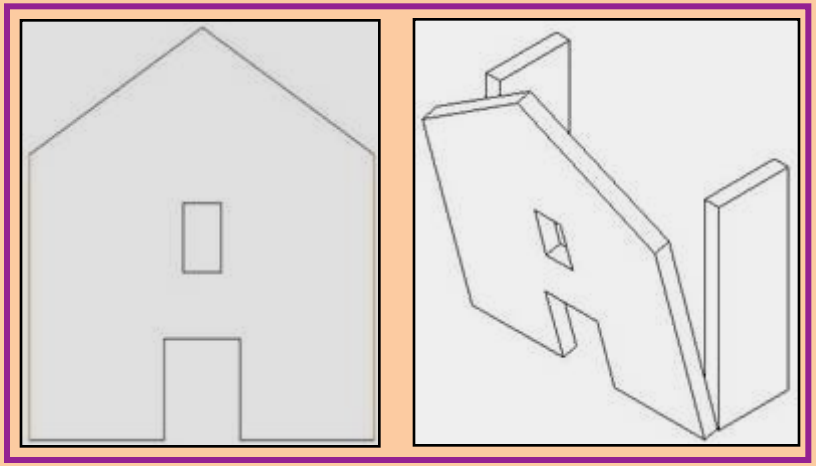
Friuli 1976

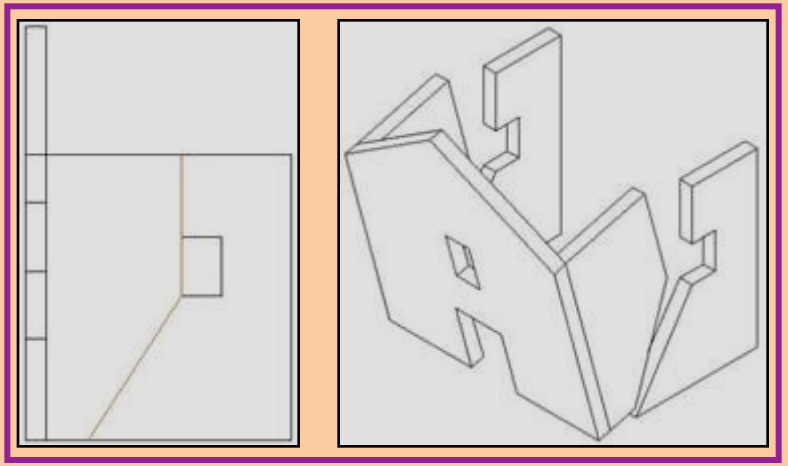


Umbria 1997

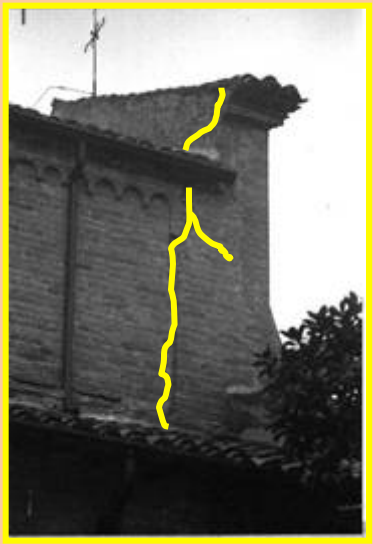
DOMINANT SEISMIC DIRECTION → **LONGITUDINAL**

Macroelement: façade





Friuli 1976



Emilia Romagna 1987

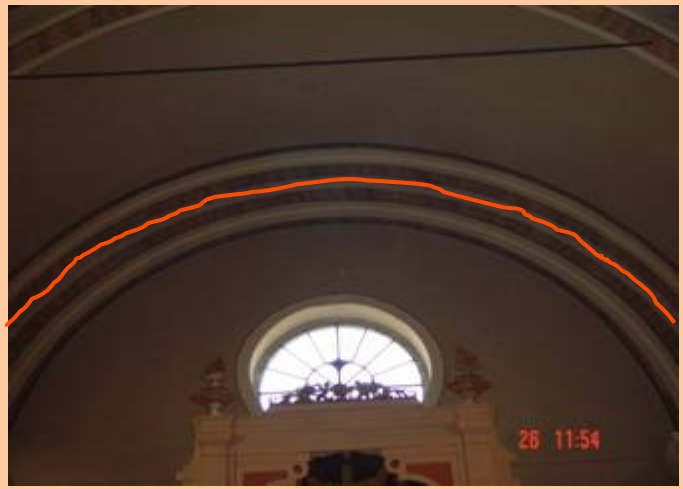
Umbria 1997

Longitudinal seismic direction ⇨ Macroelement façade: segregation mechanism

Emilia Romagna 1987

Emilia Romagna 1987

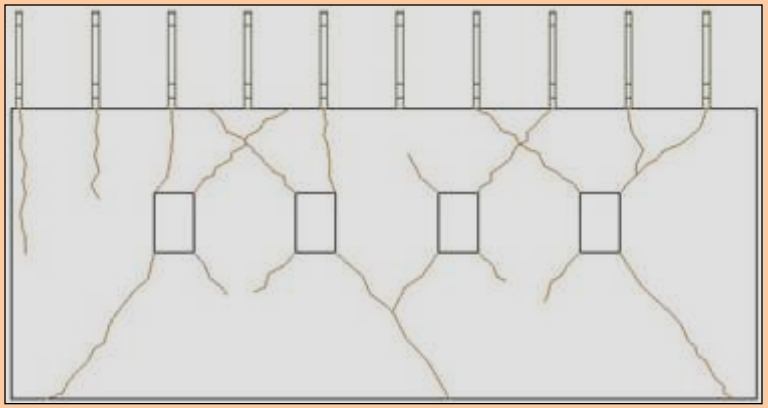
Molise 2002

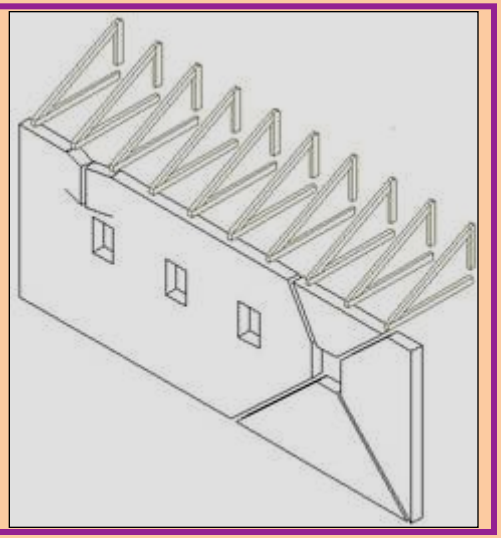


Lombardia 2004

DOMINANT SEISMIC DIRECTION → LONGITUDINAL

Macroelement: lateral wall





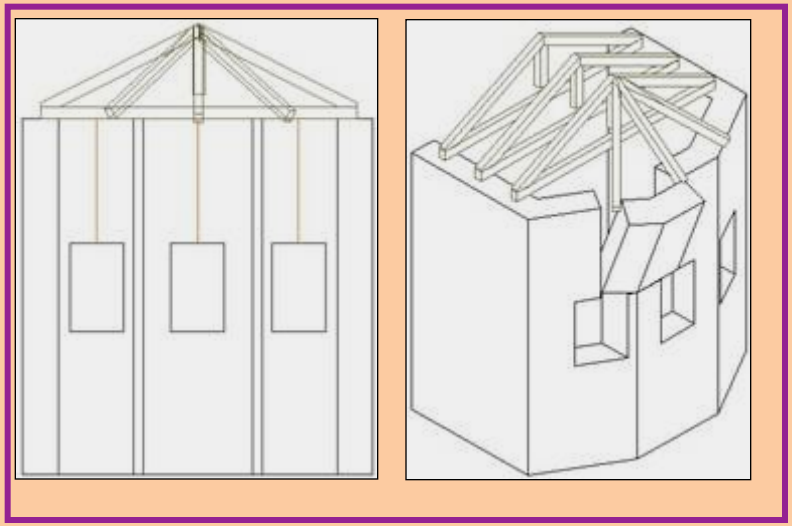
Friuli 1976

Emilia Romagna 1987

Emilia Romagna 1987

DOMINANT SEISMIC DIRECTION → LONGITUDINAL

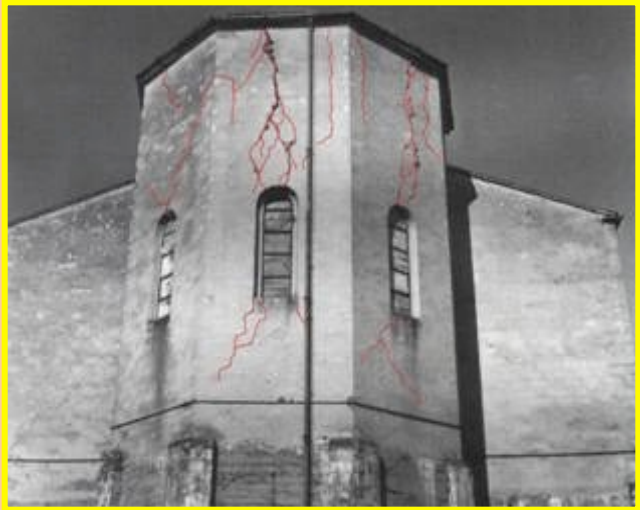
Macroelement: apse



Friuli 1976

Molise 2002

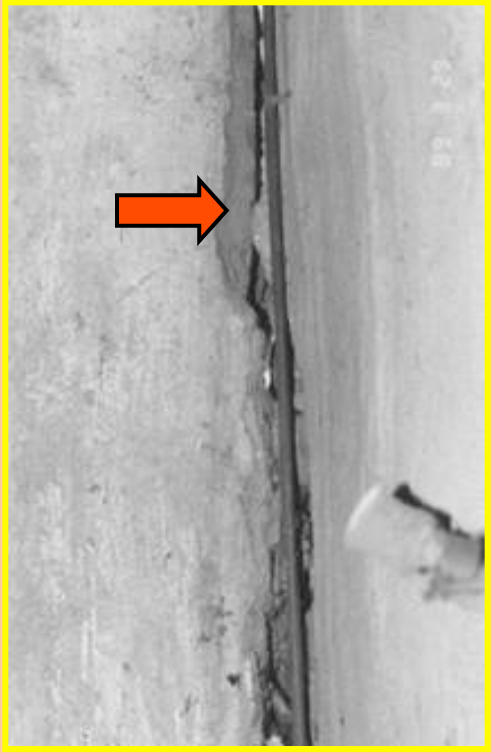
Friuli 1976



Friuli 1976

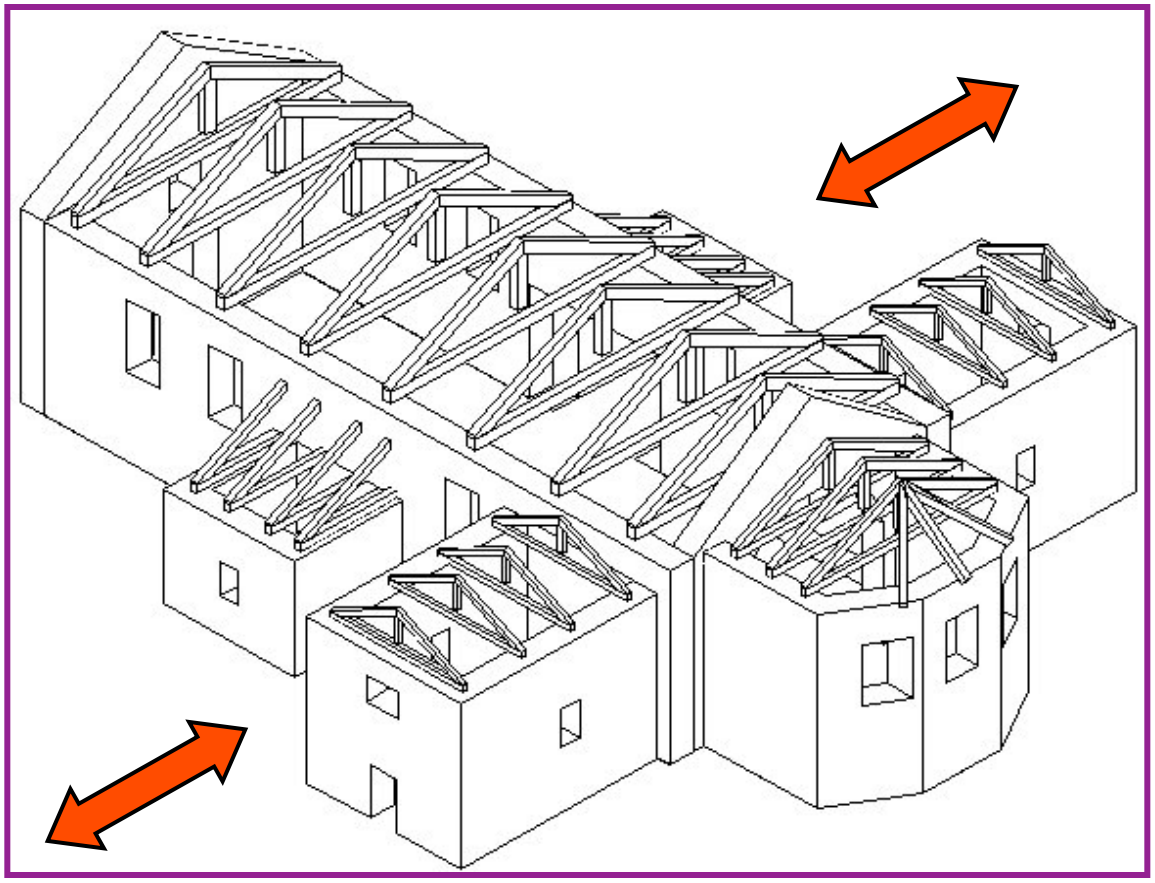
Emilia Romagna 1987

Longitudinal seismic direction → segregation mechanism

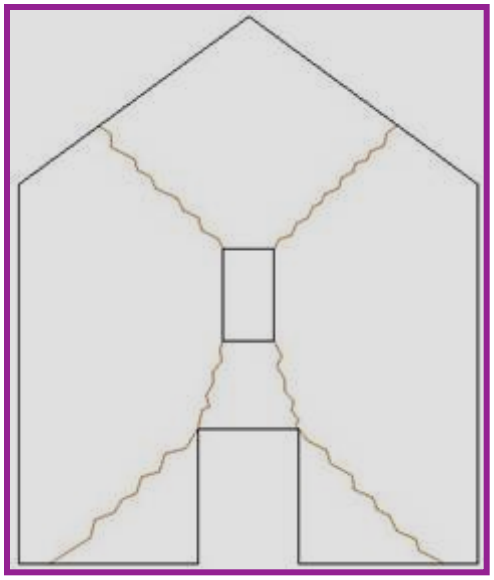


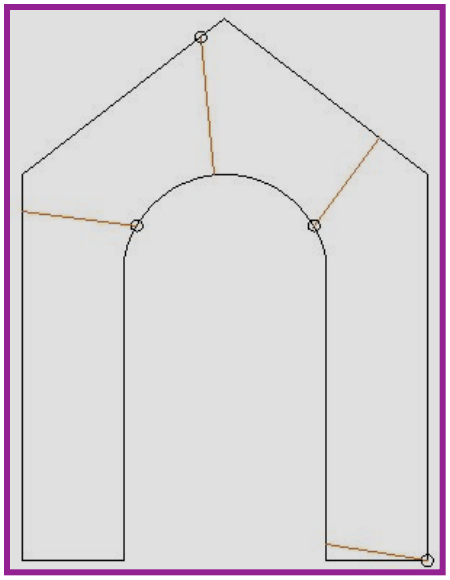
Emilia Romagna 1987

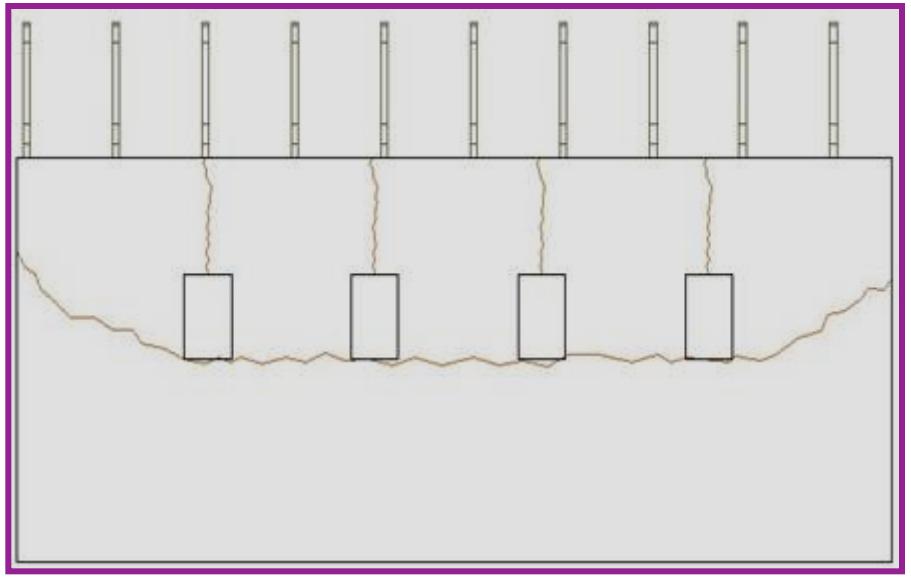
DOMINANT SEISMIC DIRECTION → **TRANSVERSAL**

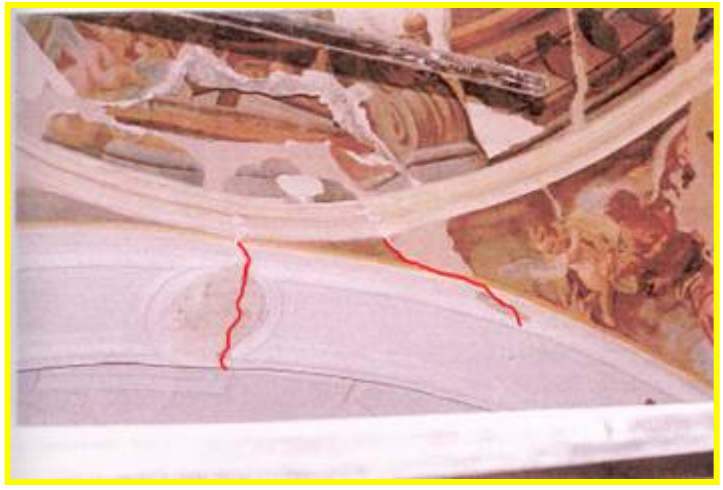


DOMINANT SEISMIC DIRECTION → TRANSVERSAL









Molise 2002

Umbria 1997

DOMINANT SEISMIC DIRECTION → TRANSVERSAL

Macroelement: façade

Friuli 1976

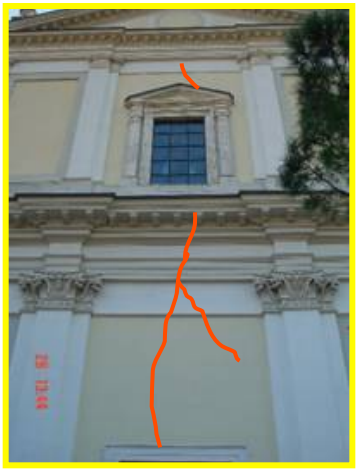
Friuli 1976

Emilia Romagna 1987

Emilia Romagna 1987

Umbria 1997

Umbria 1997

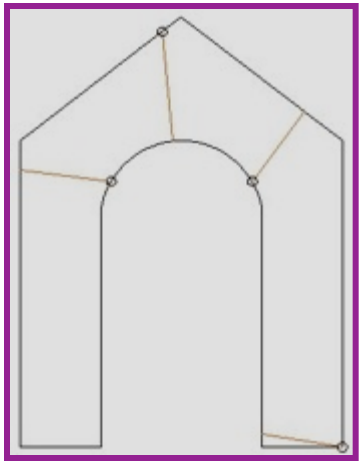


Lombardia 2004

Lombardia 2004

DOMINANT SEISMIC DIRECTION → TRANSVERSAL

Macroelement: triumphal arch



Friuli 1976

Friuli 1976

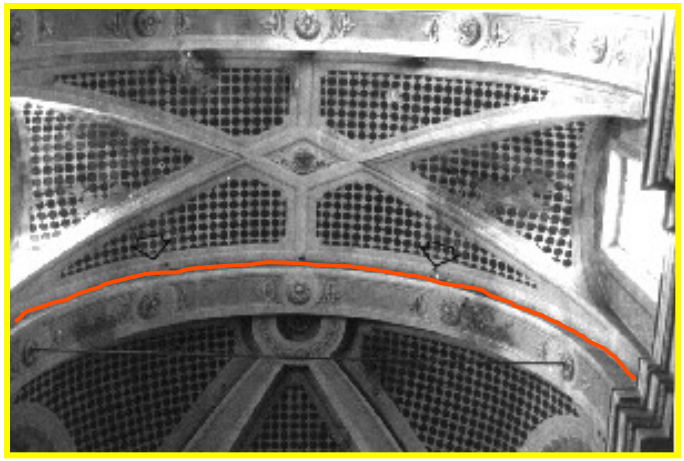
Molise 2002

Molise 2002

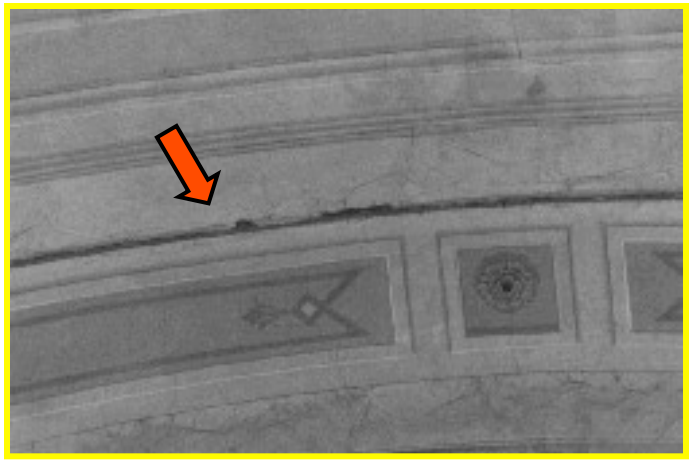
Emilia Romagna 1987

DOMINANT SEISMIC DIRECTION → TRANSVERSAL

Nave: segregation mechanism



Emilia Romagna 1987

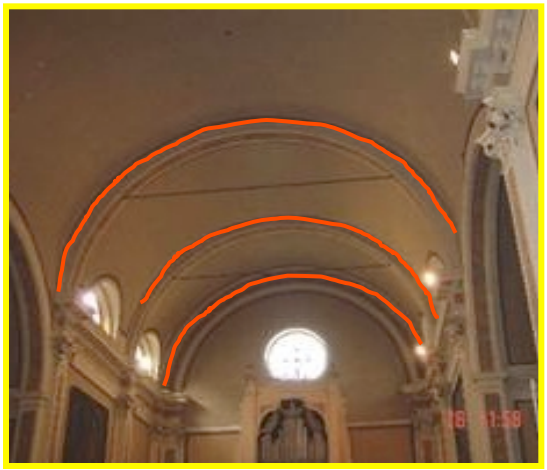


Emilia Romagna 1987

Molise 2002

Umbria 1997

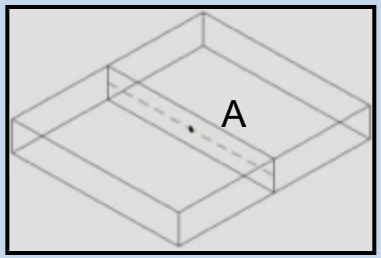
Lombardia 2004

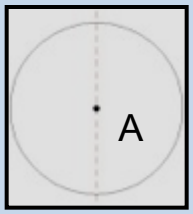


Lombardia 2004

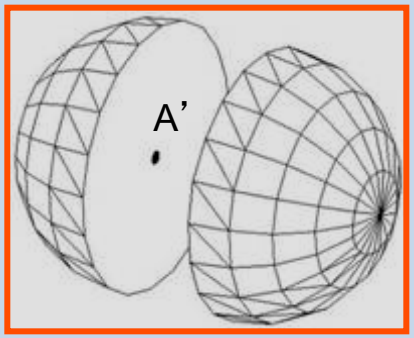
- ☑ The historical analysis of damage according to the macroelement approach is very useful to study complex buildings such as churches;
- ☑ Each macroelement has peculiar and recurrent seismic behaviour;
- ☑ The macroelement approach must include the structure evaluation “as a whole” . The comprehension of the interaction between macroelements is crucial;
- ☑ The aggregation lines among macroelements represent the transmission lines of stresses. In this way, they are not only geometric lines but also structural lines;
- ☑ Three kind of mechanism can be identified:
- ☑ 1) macroelement mechanism –2) ”segregation” mechanism between macroelements – 3) mixed mechanism, containing both the previous aspects.

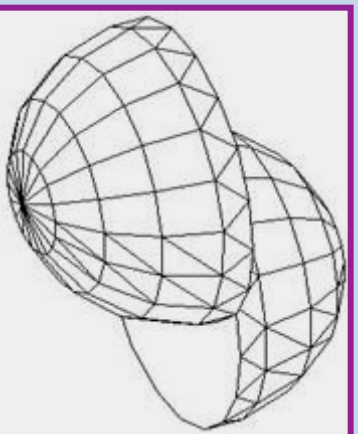
The collapse mechanism of a masonry macroelement is due to the opening of fractures (or fracture lines F.R.) which separate the macroelement in rigid blocks.





Fracture line in MODE I ⇨ **The fracture line principally causes the blocks detachments**



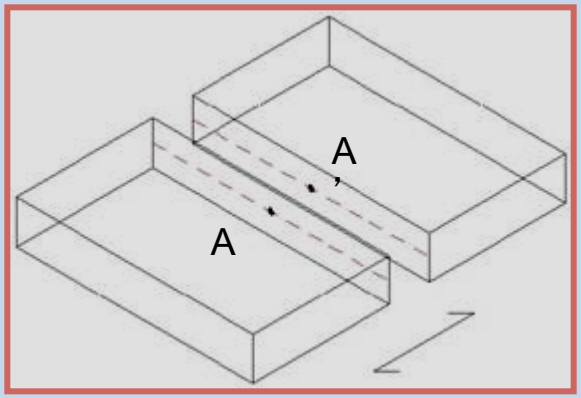


Fracture line in **MODE II** ⇨ The fracture line mainly causes relative ***<u>slidings</u>*** between blocks

MODE I

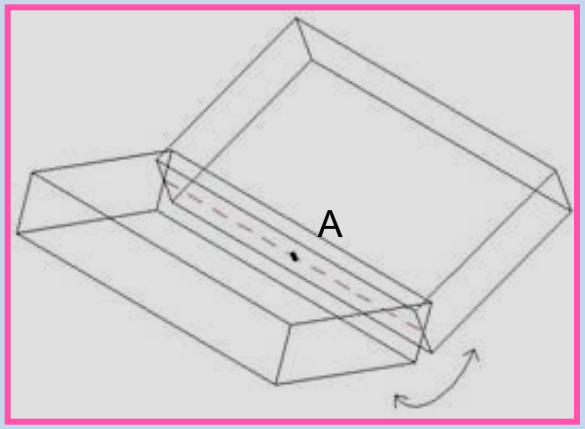
Mode Ia:

relative translation (opening) of blocks



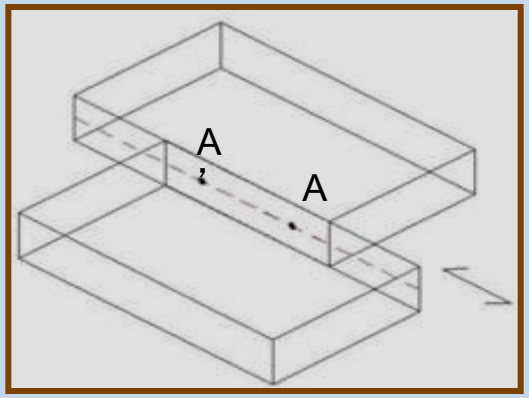
Mode Ib:

relative rotation (opening) of blocks with relative rotation centers disposed along the F.L.

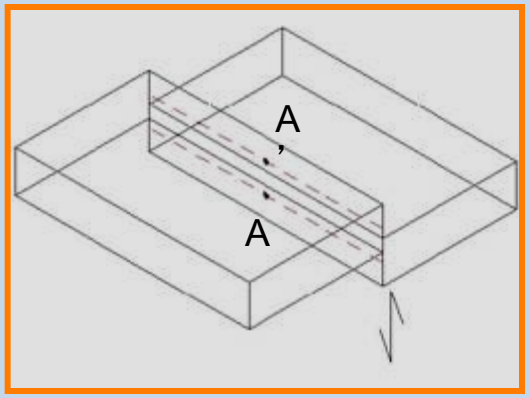


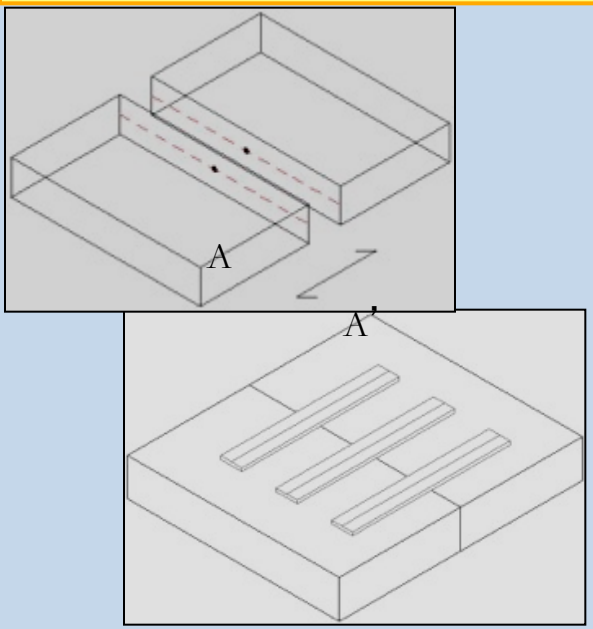
MODE II

Mode IIa:
translation of blocks along their primitive medium plan

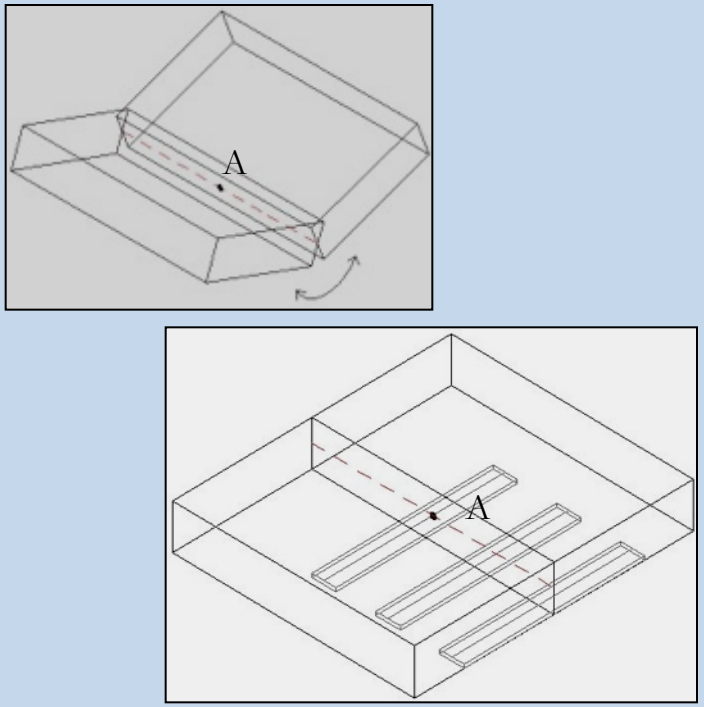


Modo IIb:
translation of blocks orthogonally to their primitive medium plan





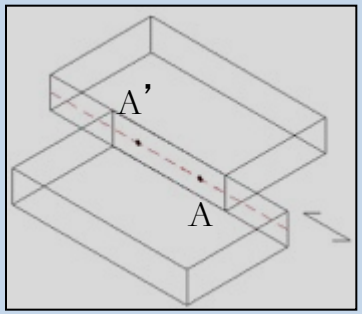
MODE Ia: FRP DESIGN

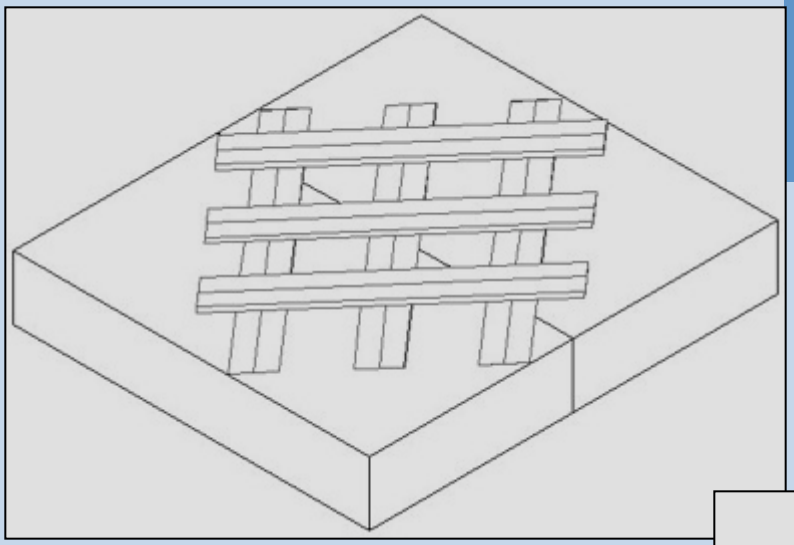


MODE Ib: FRP DESIGN

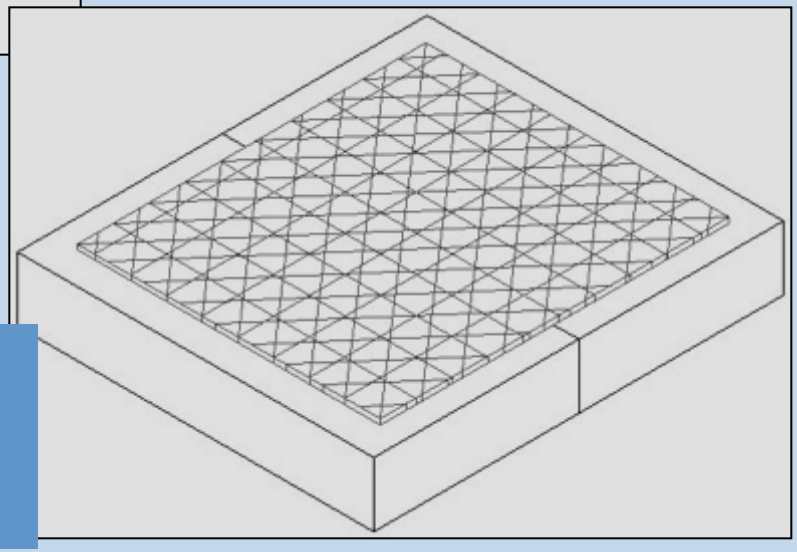
UNIDIRECTIONAL FRP STRIPS ARE APPLIED ORTHOGONALLY TO THE FRACTURE LINES.

MODE IIa: FRP DESIGN





THE TRANSLATION OF BLOCKS CAN BE AVOIDED BY OVERLAPPING ORTHOGONALLY FRP STRIPS APPLIED DIAGONALLY

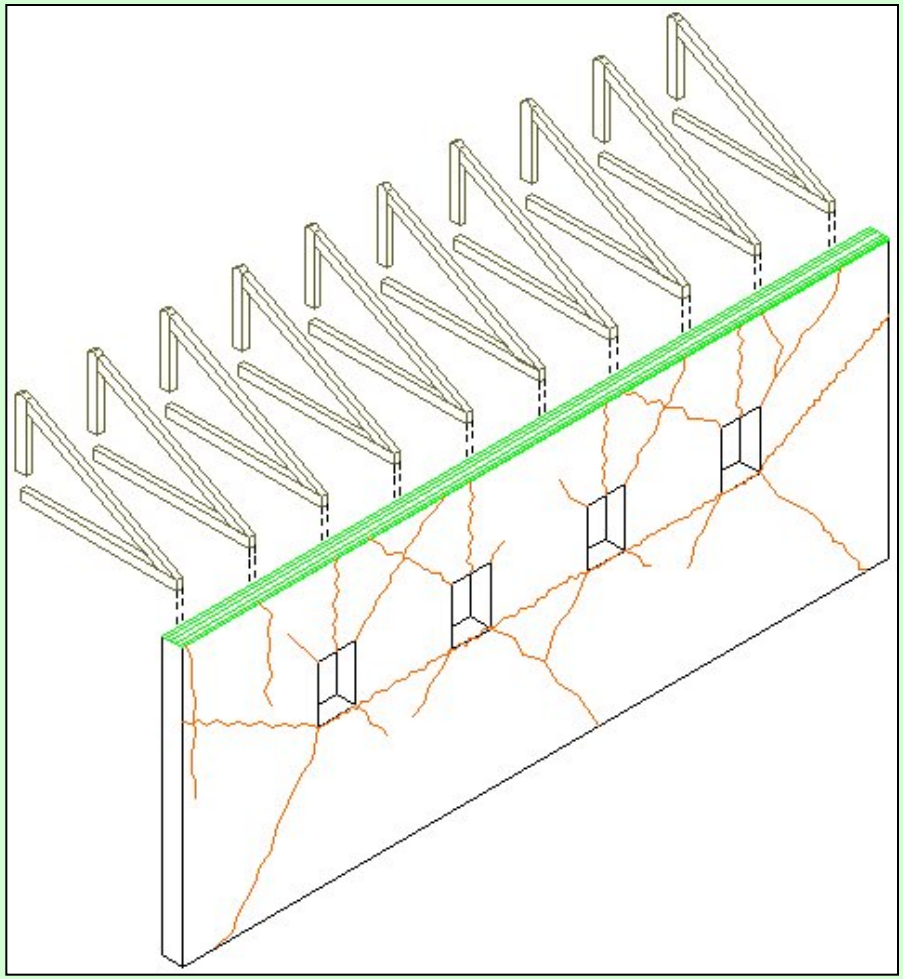


THE TRANSLATION OF BLOCKS CAN BE AVOIDED APPLYING A MULTIDIRECTIONAL FABRIC

CONSIDERING THE MODE IIb, THE USE OF FRP IS NOT FAVOURABLE, BECAUSE OF THE PROBABLE DEBONDING OF THE REINFORCEMENT

MACROELEMENT LATERAL WALL: STRENGTHENING DESIGN

CONSIDERING IN PLANE FRACTURES AS SHOWED IN THE PICTURE, FRP STRIPS OUGHT TO BE APPLIED ON THE ENTIRE WALL SURFACE. FOR ALL CASES WHERE THIS SOLUTION IS NOT ALLOWED (DESIGN NOT COMPATIBLE WITH THE RESTORATION RULES OR OTHER IMPOSSIBILITIES DUE TO THE ARCHITECTURAL ORGANISM) THE APPLICATION OF THE STRENGTHENING ON THE TOP OF THE WALL IS A VERY INTERESTING SOLUTION.

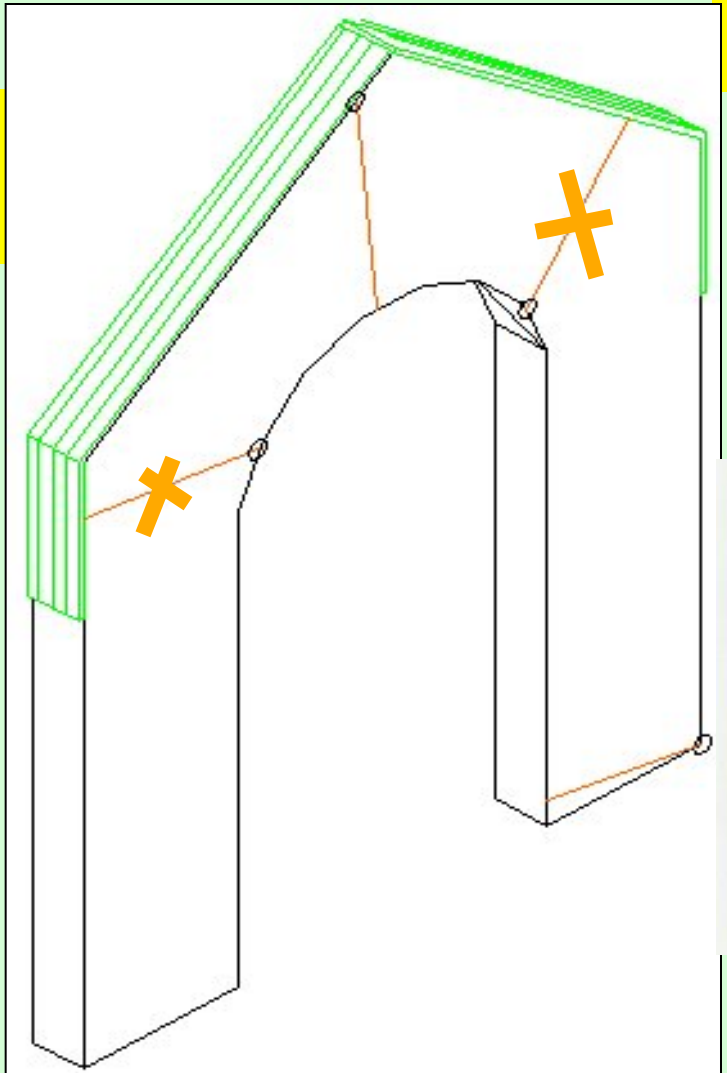


MACRO-ELEMENT "ARCO TRIONFALE"

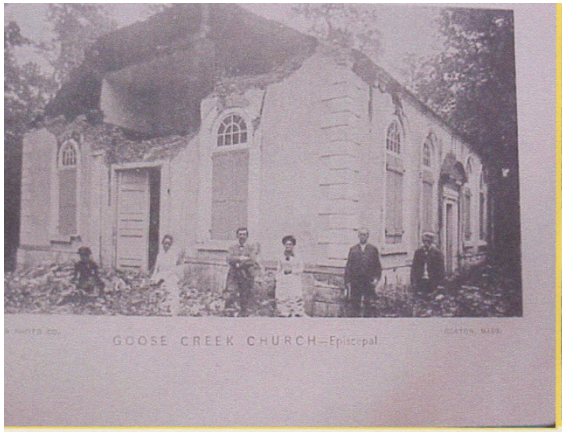
THE APPLICATION OF THE STRENGTHENING ON THE EXTRADOS OF THE ARCH IS A VERY EFFICIENT SOLUTION. ON THE OPPOSITE SIDES OF THE STRENGTHENED SURFACE NO HINGES ARE ALLOWED TO FORM. THE NEW COLLAPSE MECHANISM WILL ACTIVATE WITH A GREATER LOAD MULTIPLIER THAN THE PREVIOUS ONE.

Potential F.L. without reinforcement

Mode Ib



Mode Ib



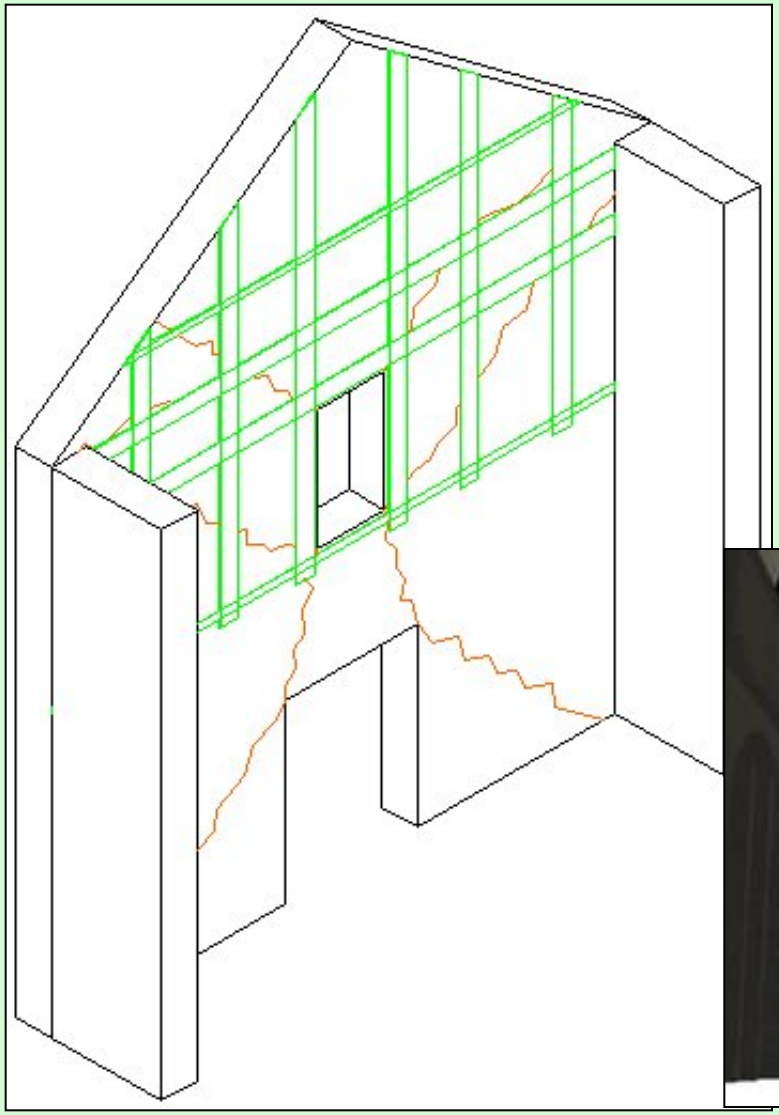
Massachusset 1886

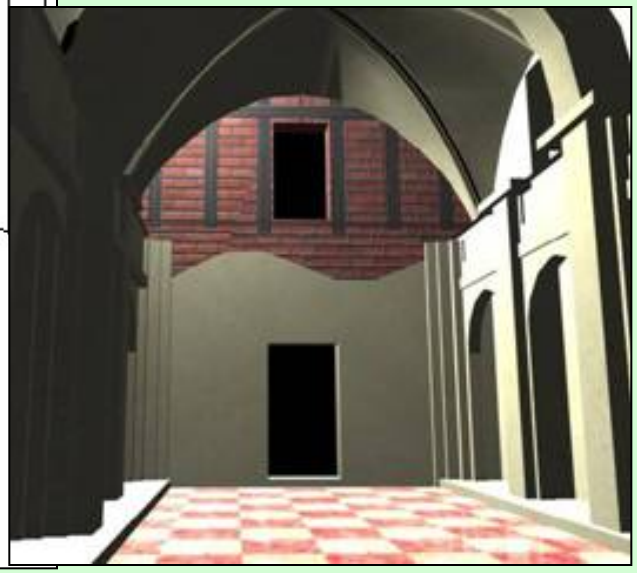
Umbria 1997

INTERAZIONE
TIMPANO DI FACCIATA-TETTO !

Emilia 2012

THE APPLICATION OF FRP STRIPS AS SHOWN IN THE FOLLOWING PICTURES CAN AVOID BOTH IN PLAIN AND OUT OF PLAIN COLLAPSE MECHANISM



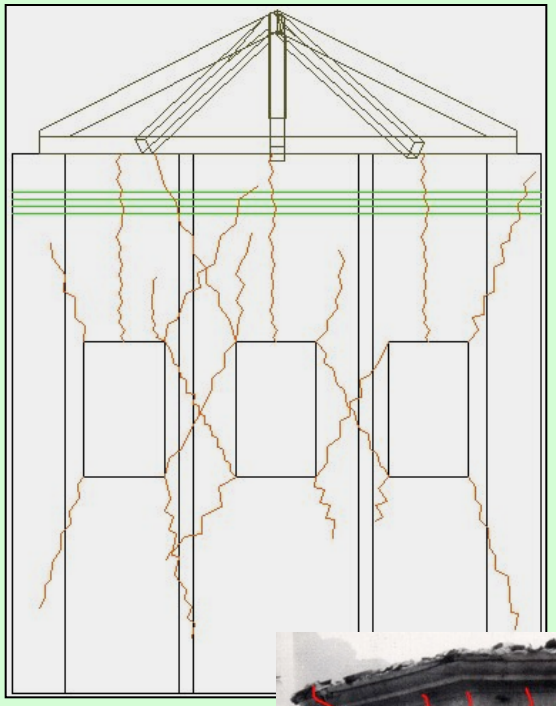


D.Bufo (PhD thesis):

3D representation of the façade strengthening design of S.Biagio's church in Modena

MACROELEMENT APSE: STRENGTHENING DESIGN

OFTEN, THE MOST EFFICIENT STRENGTHENING DESIGN FOR APSES IS TO ASSURE THE BELTING ACTION. FRP STRIPS CAN BE APPLIED IN DIFFERENT LEVELS ON THE ESTRADOS OF THE MACROELEMENT AND CAN BE COVERED BY PLASTER OR PAINT.

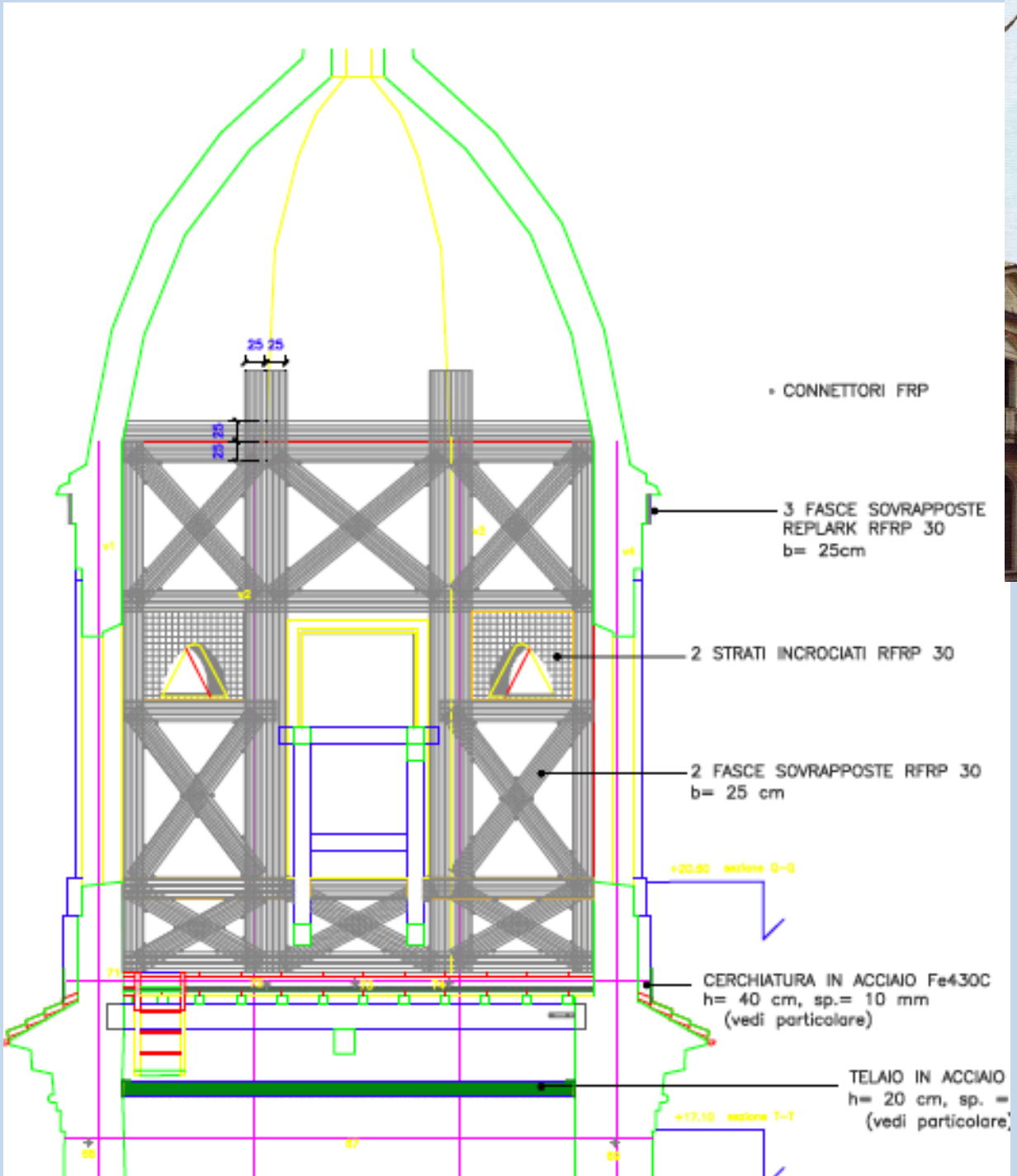


Year 1998 cFRP painted

CAMOUFLAGE

PERUGIA – CHIESA DI S. TERESA

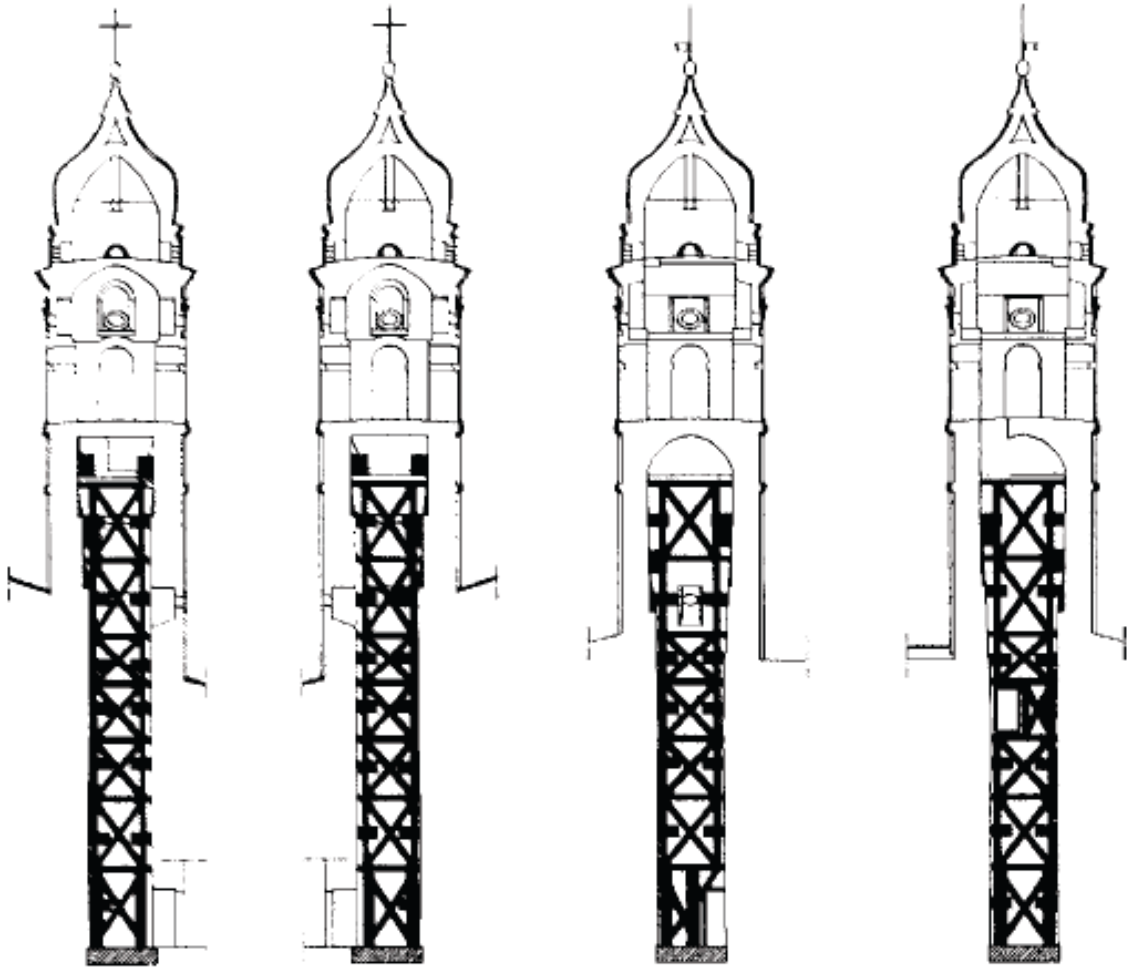
By TEC-INN



THIS PROJECT HAS BEEN
EXECUTED 2001

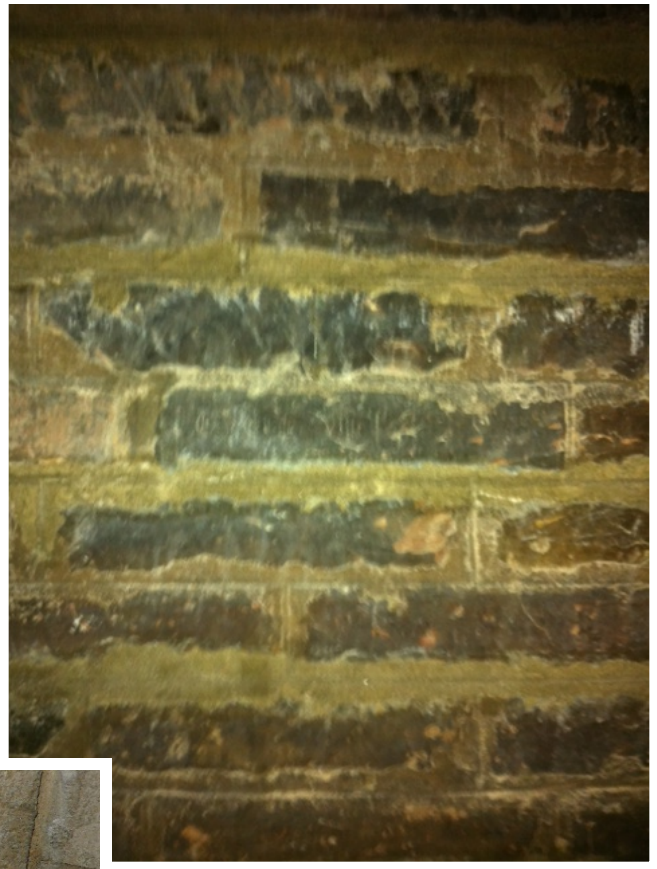
PERMANENT SOLUTION

A. DI TOMMASO 2001



15 Retrofitted “attached” Campanile with cFRP in the Region Marche (Italy). (E.Cosenza et al. 2007)

REPOINTING ARMATO con PIATTINA cFRP + MALTE



Paramenti interni della torre Ghirlandina a Modena

Arch Cadignani COMUNE DI MODENA

TORRE GHIRLANDINA

CUCITURA LESIONI PSEUDO=VERTICALI

Tecnica della ristilatura armata con cFRP

Piattina pultrusa di carbonio come armatura
Malta di calce come intasatura intermedia.
Malta di resina come intasatura terminale.


2012/11/29


2012/11/29

RE-CONSTRUCTION

After seimic collapse to ***rebuilt as it was before*** It is silly

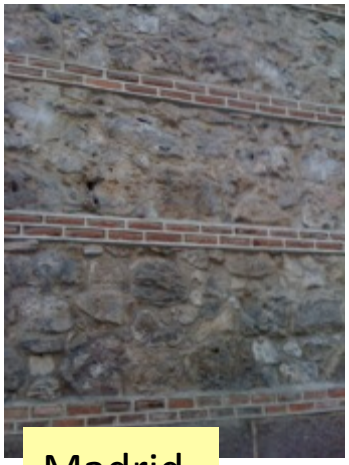
Dopo il collasso sismico ricostruire come era non è saggio.

The common feeling links the “as it was” only to appearence,
then there is possibility to rebuilt strengthening the construction.

Il comune sentire lega il com’era soltanto alla apparenza, vi è spazio di ricostruire rinforzando la costruzione senza modificara la apparenza e il suo funzionamento statico originale in condizioni usuali, riservando una risposta **adeguata** in condizioni eccezionali

It. MURATURA LISTATA

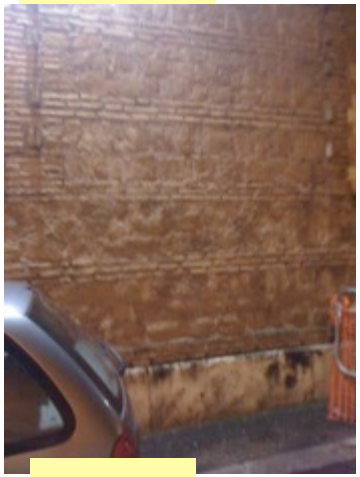
BANDED MASONRY



Madrid

Ss TRINITA' ABBEY - VENOSA (POTENZA)

SANT JOAN BARCELONA



Roma

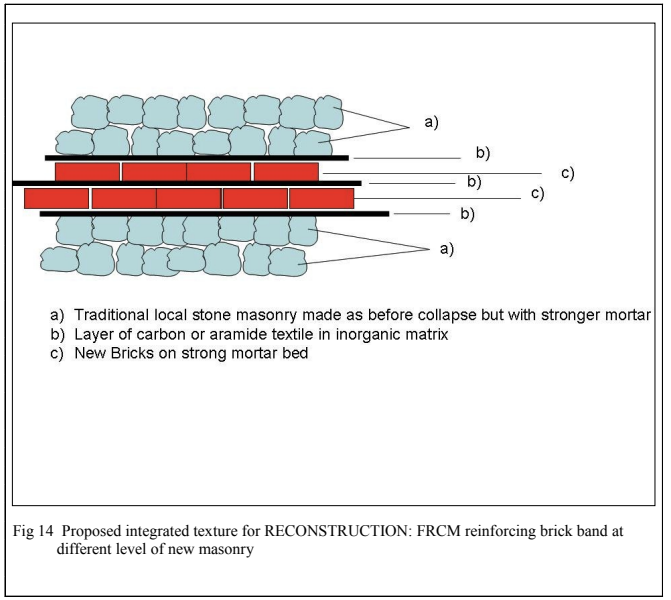
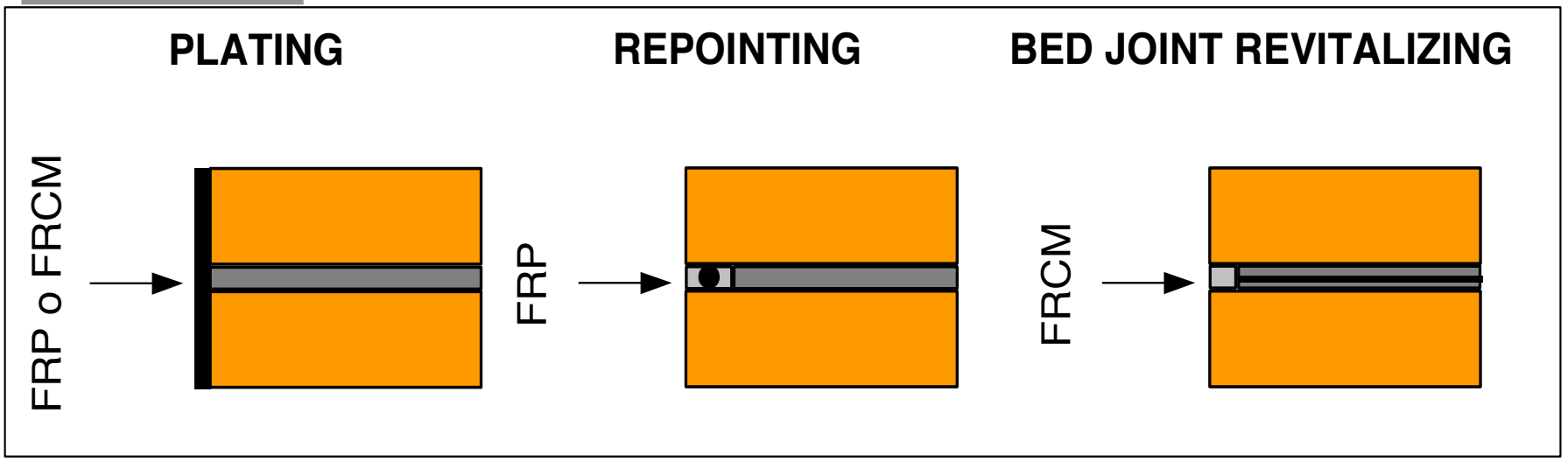


Fig 14 Proposed integrated texture for RECONSTRUCTION: FRCM reinforcing brick band at different level of new masonry

BANDED BRICK MASONRY REINFORCED WITH FRCM

FUNDAMENTAL TECHNIQUES FOR HISTORICAL CONSTRUCTION STRENGTHENING with FRP or FRCM



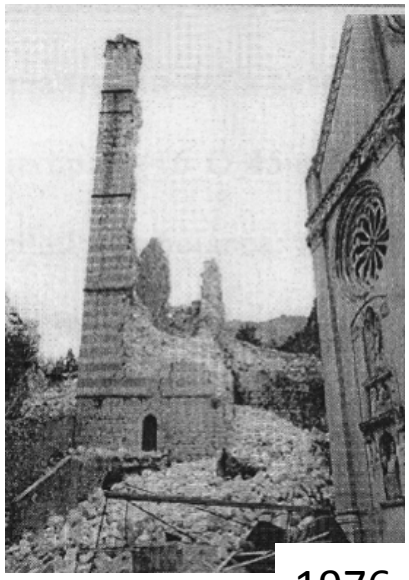
Majano UDINE 1976

2012

Dove era
Non come era

Where it was and no how it was

Donde estava y
N O N **como era**



1976

Fig. 122 - *Il campanile* in corso di restauro, da notare l'esecuzione del paramento a pietra vista, l'anima interna del muro in cemento armato, il muro di mattoni che fa da cassaforma nella canna interna.

Gemona UDINE

2012

Dove era
Sembra
come era

Donde estava y
PARECE **como era**

Where it was and seems how it was